GREAT SALT LAKE

An Overview of Change

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SALT LAYDOWN PROJECT - REPLENISHMENT OF SALT TO THE BONNEVILLE SALT FLATS

by

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ABSTRACT

Reilly Industries, Inc. and U.S. Bureau of Land Management have been conducting a Salt Laydown Project to increase the salt-crust thickness of the Bonneville Salt Flats. The project began delivering sodium chloride brine to Bonneville Salt Flats in November 1997. The objective of the five-year experimental Salt-Laydown Project was to add up to 1.5 million tons of salt to Bonneville Salt Flats each year of the experiment. Three years of Laydown-Project operation have demonstrated that annual salt-tonnage loss from Bonneville Salt Flats can be replenished by the laydown facility. During this period, a sodium chloride salt mass of 4.6 million tons was delivered to Bonneville Salt Flats. The average annual addition of 1.5 million tons exceeded an estimated annual salt loss of 0.85 million tons. The salt addition appears to be distributed between the existing salt-crust, a new salt-crust area, and the shallow-brine aquifer.

Monitoring during the project included measurement of changes in salt-crust thickness, areal extent, and mass. Ten test pits showed that at least five different strata comprise the salt crust. Thickness measurements of the dense-cemented halite stratum (surface stratum of the salt crust), and the cemented-coarse-porous halite stratum (sub-surface stratum), showed substantial thickness changes from year to year, while little change in total salt-crust thickness was observed at nine locations during a 10-year period. Based on thickness comparisons from 1994 through 2000, the dense-cemented halite stratum thickness increased at one location and decreased at three other locations. However, cemented-coarse-porous halite stratum thicknesses increased when the dense-cemented halite stratum thicknesses decreased at the same locations. An unusually wet (or dry) year could measurably decrease (or increase) the thickness of the dense-cemented halite stratum from year to year. This yearly variation in thickness could occur despite the increased salt tonnage added to Bonneville Salt Flats by the Laydown Project. Although the yearly added tonnage would maintain or increase the current mass of sodium chloride in the salt-crust deposit and shallow-brine aquifer, annual variation in dense-cemented halite stratum could easily mask the annual 0.4-inch increase in salt-crust thickness predicted by the 1991 Laydown Project feasibility study.

An estimated 5-square mile increase in salt-crust areal extent was observed between September 1997 and October 1999. Based on assumed changes in thickness of 0.25 to 1 inch, and bulk salt densities of 79.4 and 109.8 pounds per cubic foot, as much as 0.6 million tons of salt were added to the new salt-crust area by the Laydown Project. The remaining 4 million tons were apparently distributed to the main body of the salt crust (26 square miles in 1997) and the shallow brine aquifer (the tonnage actually distributed to each is currently unknown).

Geochemical modeling of brine compositions, determined during the project, produced several observations regarding salt additions to the salt crust and shallow-brine aquifer. The TEQUIL model accurately predicted brine chemistries, based on agreement between modeled output and solar-pond brine compositions from a commercial potash operation. The model also showed that the shallow-brine aquifer has the capacity to assimilate an additional 17 to 25 million tons of sodium chloride. This tonnage is four to five times the 4.6 million tons of laydown salt delivered to Bonneville Salt Flats during the first three years of the Laydown Project. The ability of the shallow brine aquifer to assimilate additional salt may help account for the laydown-delivered salt tonnage that was in excess of the amount estimated in the 5 square miles of new salt crust.

The laydown sodium chloride mass assimilated into the shallow-brine aquifer is expected to eventually be redistributed in the salt crust as part of new surface and additional subsurface halite crystal growth. TEQUIL also predicted that the addition of laydown brine to the shallow-brine aquifer does not change the salt-crust mineral assemblages. Anhydrite and halite are the only minerals predicted to precipitate from two different mixing ratios of laydown brine and shallow aquifer brine in an open system such as Bonneville Salt Flats. Potassium and magnesium salts do not precipitate in the open system of the Bonneville Salt Flats salt crust because the addition of rain water or the shallow-aquifer brine dissolves them immediately. All TEQUIL simulations showed that more than 90 percent of the water would have to be evaporated, and 96 to 98 percent of the sodium chloride would have to be precipitated before potassium and magnesium minerals precipitated from the brine. This condition could only be achieved if a mixture of laydown brine and shallow-aquifer brine were isolated from the shallow-brine aquifer and subjected to conditions similar to a commercial solar-pond process.

INTRODUCTION

The Bonneville Salt Flats (BSF) is located in the western part of the Great Salt Lake Desert of northwestern Utah. BSF is part of a large playa that occupies one of several enclosed sub basins that comprise the Great Salt Lake Desert (figure 1). These sub-basins include the Bonneville Salt Flats, Pilot Valley, and the Newfoundland Basin. BSF is roughly divided into a north and south half by the east-west-trending Interstate Highway 80 (I-80) and the adjacent Western Pacific Railroad right-of-way (now Union Pacific) which is parallel to, and 1,400 feet south of I-80. The north half of BSF is dominated by public land, while the south half is mainly private. The twin cities of Wendover, UT and Wendover, NV are adjacent to I-80 and about 4 miles west of BSF's western margin. The economic potential of potash-bearing brines beneath the surface of BSF was recognized as early as 1914, and commercial potash (KCl) production from these brines has been continuous since 1939 (Bingham, 1980, p. 230-231).

BSF is listed on the National Register of Historic Places as site of world land-speed records. Because of its unique geologic characteristics, BSF was designated by the U.S. Bureau of Land Management (BLM) as an Area of Critical Environmental Concern (ACEC). Historic activities and unique physical characteristics have made BSF an area of national and international interest.

The BSF sub-basin is geologically and hydrologically complex, and this complexity is reflected by both seasonal and yearly variation in salt crust areal extent and thickness. Variation of salt-crust area and thickness has been documented since 1927. Early measurements made by Nolan (1927, p. 34) in 1925 indicated that the salt crust (north and south halves) covered about 150 square miles, and had a measured thickness of 3.5 feet near Salduro Station (9 miles east of Wendover on the Western Pacific Railroad). Using Nolan's map of "crystalline salt" (1927, Plate 3), Turk (1978, p. 9) estimated that the 1925 salt-crust area north of the Western Pacific Railroad was 68 square miles. For comparison, Turk (1978, p. 9-11) also documented 22 salt-crust area measurements that were taken during 1972-1976 from BSF north of the Western Pacific Railroad. The average area from the 22 measurements was 47 square miles, while minimum and maximum areas were 38 and 56 square miles respectively. Lines (1979, p. 2) measured a salt-crust area of about 40 square miles during fall 1976, of which 30 square miles were perennial salt crust with thicknesses of 1 to 3 feet (estimated from Lines, 1979, p. 30, 45-56). Mason and Kipp (1998, p. 1) reported a measured salt-crust area of 43 square miles in late summer 1992; of the 43 square miles, about 34 square miles were perennial salt crust with thicknesses of 1 foot or more. Lines (1979, figure 11) and Mason and Kipp (1998, figure 26) show these areas were based on measurements of salt crust exposed north of the Western Pacific Railroad and I-80.

Reported depletion of salt-crust thickness has been a concern to the public and land-managing agencies for at least 26 years (McMillan, 1974, p.1; Lines, 1979, p. 4). This concern is based on salt-crust area and volume changes reported between 1960 and 1988, that were measured north of the Western Pacific Railroad and I-80. McMillan (1974, p. 3) reported a 9 and 15 percent respective decrease in salt-crust

Figure 1. *Great Salt Lake Desert showing sub-basin locations (Bonneville Salt Flats, Pilot Valley, and Newfoundland Basin), western Utah.*

area and volume from 1960 through 1974. Brooks (1991, p. 8) calculated a 20 and 30.6 percent respective decrease in salt-crust area and volume from 1960 through 1988.

A more recent study by the U.S. Geological Survey (USGS) suggested that an estimated 850,000 tons of salt could be lost annually from the north half of BSF (Mason and Kipp, 1998, p. 106). The USGS estimate was based on an annual brine withdrawal of 1,500 acre feet from a federal-lease collection ditch located east of the salt crust. Salt tonnage was derived from computer simulations that used data collected from BSF from 1991 through 1993. This estimate is in reasonable agreement with Reilly Industries, Inc.'s (Reilly) annual production from the same lease collection ditch; a range of 0.49 to 1.03 million tons per year of salt

were removed during the period from 1995 through 1998 (A. Frye, Chief of Counsel, Reilly Industries, Inc., personal communication, May 19, 1999).

Because the BLM, Reilly, and the racing community (represented by "Save the Salt" [STS]) are concerned about the reported deterioration of the BSF, they are attempting to replenish salt to the BSF through cooperative agreements. In 1991, Reilly and STS jointly funded a salt-replenishment feasibility study that resulted in a salt-laydown facility plan (Bingham, 1991). According to the plan, sodium chloride brine would be pumped out onto the BSF at a rate of 6,000 gallons per minute (gpm), 24-hours per day, for six months (November - April) during each year of the program. This experimental program was anticipated to have an initial life of at least five years. Based on the engineering design, up to 7.5 million tons of salt could be deposited during a five-year period over a 28-square mile area. According to Bingham (1991, p. 2), this would result in an additional salt-crust thickness of about 0.4 inches per year.
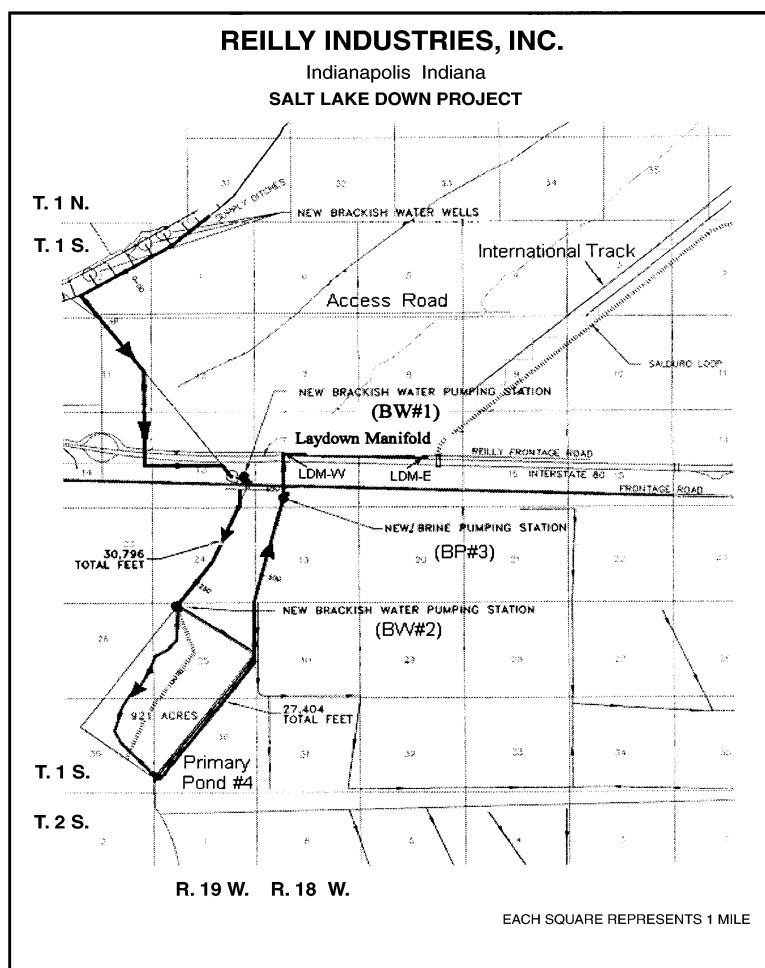
Based on the 1991 salt-replenishment feasibility study, BLM and Reilly entered into a salt-laydown agreement in 1995. Under the laydown agreement, Reilly financed the installation and operation of a $1,000,000 salt-laydown facility, and BLM and Reilly initiated a cooperative monitoring agreement to measure the amount of salt delivered to BSF each year of the program. To ensure the pumped brine meets salt-laydown-design specifications, Reilly and BLM independently sample and analyze the brine being pumped onto BSF. The Laydown Project began delivering brine to BSF on November 1, 1997.

Figure 2. *Index map showing location of Reilly Laydown facilities with respect to Interstate 80 and Bonneville Salt Flat features (for example, Salduro Loop, International Track, and county access road. Arrows on ditches show water-flow direction (after Reilly Industries, 1997).*

OBJECTIVES

This paper describes the first three years of the Laydown Project, and includes the November through April pumping periods of 1997 to 1998, 1998 to 1999, and 1999-2000. The objectives of this report are to: 1) describe components and operation of the salt laydown facility, 2) summarize BSF and laydown monitoring methods, 3) explain and quantify results of the Laydown Project's first three years, and compare them with BSF baseline data, 4) compare pre- and post-laydown salt-crust thicknesses and areal extents, and 5) evaluate the effects of mixing laydown brine with shallow-aquifer brine using the TEQUIL model.

LAYDOWN FACILITY DESCRIPTION

The laydown facility (figure 2) is composed of brackish-water supply wells, about 11 miles of transfer ditches and associated pumps, a 921-acre bedded salt deposit (primary pond no. 4 [PP no. 4]), and a brine-distribution manifold. Because the ditch system and the brine-distribution manifold traverse a 13-mile distance over flat terrain, the biggest challenge is to move water from one end of this flat area to the other. The following description of the laydown facility shows how this water movement is accomplished.

Brackish water is obtained from seven alluvial-fan wells on the south flank of the Silver Island Range (water contains from 6.2 to 8 g/L TDS [Mason and Kipp, 1998, p. 49] compared with shallow-brine aquifer which averaged 244 to 297 g/L TDS during 1994-2000). From these wells the brackish water is pumped into a series of transfer ditches that move water south and under I-80, a distance of about 4.5 miles. To keep the brackish water flowing, brackish-water pump no. 1 (BW no. 1) was installed in the transfer ditch south of I-80. A second pump (brackish-water pump no. 2 [BW no. 2]) was installed 1.5 miles south of BW no. 1. With the aid of BW no. 1 and BW no. 2, brackish water is ultimately delivered through a 24-inch diameter discharge pipe into the northwest corner of primary pond no. 4 (PP no. 4) where the salt dissolution process is initiated.

PP no. 4 is an old solar-evaporation pond that was used to precipitate NaCl (as the mineral halite) from potassium-bearing brine during the economic mineral-recovery process. NaCl in the 921-acre pond is approximately 3 to 4 feet thick, and totals about 8 million tons. During its residence time in PP no. 4 (about 15 to 30 days), the brackish water dissolves as much as 2 lbs of salt per gallon, and the density of the resulting brine approaches 1.2 g/mL (sodium chloride saturation).

From the southeast corner of PP no. 4, the brine flows

through a north-trending, 3.3-mile transfer ditch that termi-
nates at brine pump site no. 3 (BP no. 3, figure 3). Brine is
lifted approximately 11 feet vertically above the collection
ditch by the active pump and discharged into a 5-foot wide,
7-foot long, 7-foot high concrete vault. Pumping the brine
into the concrete vault provides sufficient hydraulic head for
the brine to flow north for a distance of about 0.4 miles
through a 24-inch diameter discharge pipe. The north-trend-
ing discharge pipe passes under I-80 and discharges brine
into the west end of a brine-laydown manifold. The laydown
manifold is an east-west-trending, 1.5-mile long, 30-foot
wide area between west-bound I-80 and a parallel frontage
road. Using a brine-density range of 1.14 to 1.18 g/mL, an
average brine flow rate of 6,688 gpm would deliver about
350 to 485 tons per hour (tph) of NaCl to the brine-laydown
manifold. Brine flows north from the manifold onto BSF
through twelve culverts that are uniformly spaced along the
manifold's length.   Values for tph were calculated using
equations 1-3 in White and Wadsworth, 1999, appendix 3, p.
A3-1; densities of 1.14 and 1.18 g/mL correspond with NaCl
wt percent values of 18 and 24, and were determined from
linear regression of daily laydown-brine density and NaCl wt
percent values (n=70, r^2=0.976; White and Wadsworth,
1999, appendix 3, tables A3.1, A3.5, and A3.6).
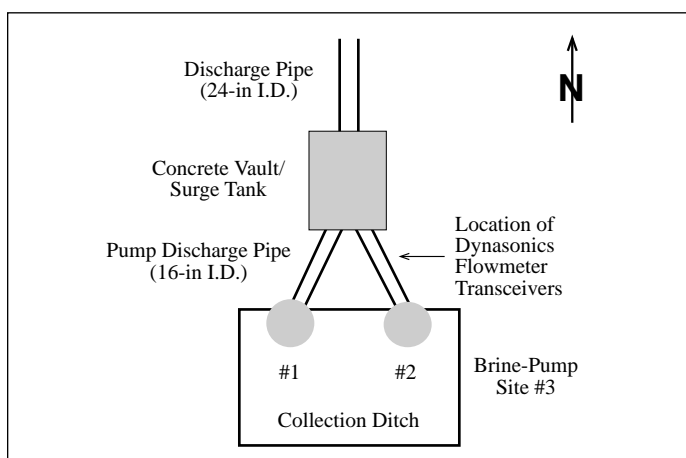
Figure 3. *Plan view of brine-pump site no. 3; pump no. 2 is active,
and pump no. 1 is standby.*

METHODS

Pre-1994 Monitoring Well Database

Three USGS studies of BSF were conducted from 1976
through 1993:   1976 through 1978 (Lines, 1978; 1979),
1981, and 1991 through 1993 (Mason and others, 1995;
Mason and Kipp, 1998). Chemical analyses of 186 monitor-
ing-well samples from these studies (appendix A1) are used
in this paper as an historical comparison with 1994 through
2000 BLM monitoring-well sample analyses. Four different
well-numbering systems were used to identify four groups
composing the 186 samples (well numbers prefixed by
"USGS/BLM", "B", "K", and "L"). These systems are de-
scribed below and listed in table 10.
The system of numbering wells in Utah is based on the
cadastral land-survey system of the U.S. Government, and is
described by Lines (1978, p.1-2) and Mason and Kipp (1998,

p. 6).   Although USGS uses this method as their primary
well-numbering system, the primary system for BSF is com-
monly linked with a secondary alpha-numeric system char-
acterized by a "USGS" and/or "BLM" prefix (that is, the pri-
mary well number [B-1-17] 11aac-1 is equivalent to USGS-
2/BLM-60). To simplify well labeling for figures and tables
presented in this paper, the "USGS" and/or "BLM" alpha-
numeric system is used instead of the primary numbering
system. The 186 samples identified by the "USGS" and/or
"BLM" alpha-numeric identification system, are listed in
appendix A1.
Monitoring-well sample data from Lines (1978) are
numbered with "USGS" and "K" prefixes (figure 4). Con-
servation Division sample data are numbered with "B", "K"
and "L" prefixes (figure 5). Sample data from Mason and
others (1995) are numbered with "USGS and/or BLM" pre-
fixes (figure 6). Monitoring-well numbers starting with "K"
represent shallow wells (19- to 23-feet deep) that were hand
augered during 1965-1967 (Turk, 1969, p. 64-65), and sub-
sequently sampled during the Lines and Conservation Divi-
sion studies. Conservation Division well numbers prefixed
with "B" or "L" were shallow auger holes drilled to depths
of 10 feet or less during 1981 (J. F. Kohler, Geologist, BLM
Utah State Office, personal communication, June 29, 2000).
Chemical analyses from the 186 monitoring wells that
were 25-feet deep, or less, were compared with the 1994
through 2000 BLM monitoring-well sample analyses. Molar
concentrations were calculated for each of the major ions
(Na, Mg, K, Ca, Cl, and SO_4) listed in the analyses of 186
samples. The resulting molar concentrations were averaged,
and the results used to determine average mole ratios of
K/Mg, Cl/Na, and SO_4/Ca for each of the four USGS well-
numbering systems listed in table 10.

1994-2000 Monitoring Well Sampling and Analyses

BLM started collecting annual BSF shallow-brine
aquifer samples in 1994. The purpose of the sampling pro-
gram was to identify historical trends, and make yearly com-
parisons between BSF-brine and current laydown-brine
chemistry, so that future effects of the project on the natural
system could be measured. The brine samples were taken
during an August-September period from a suite of 27 mon-
itoring wells in the shallow-brine aquifer. This period was
selected because effects of evaporation on BSF are histori-
cally greatest at this time of year, and maximum yearly brine
concentrations would be expected; because most of the pre-
1994 samples were collected during the same period, com-
parisons could be made. Because the depth of the shallow-
brine aquifer has been reported as ranging from 15 to 25 feet
(Turk, 1973, p. 8; Lines, 1979, p. 65; Mason and Kipp, 1998,
p. 22), wells included in the 27-well suite have depths of 25
feet or less (BLM-27 is the only exception with a measured
depth of 27.7 feet).   These 27 wells were also selected
because of their proximity to the International Track and the
federal-lease collection ditch and are shown in figure 7.
Samples have been collected during Fiscal Years 1994, 1995,
1996, 1997, and 2000 (the period October 1 through Sep-
tember 30 of the next year - FY94, FY95, FY96, FY97, and
FY2K). Although BLM's original intent was to sample the
same wells each year, changes in accessibility and loss of
some surface casings (for example, USGS-9 and BLM-60)
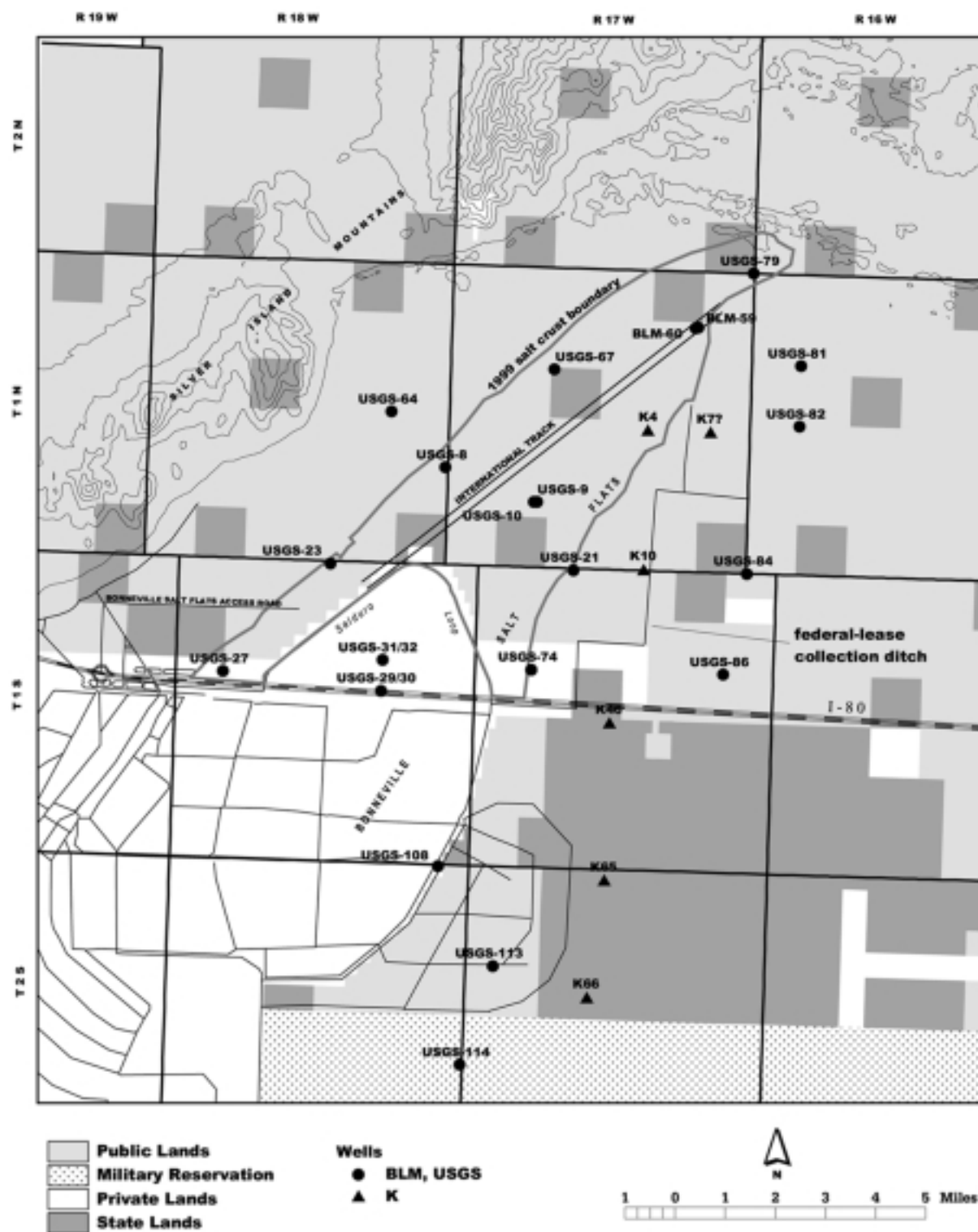
Figure 4. *Location of 1976-78 USGS monitoring-well samples (Lines, 1978-1979). Well sites are identified by "USGS" and "K" prefixes.*
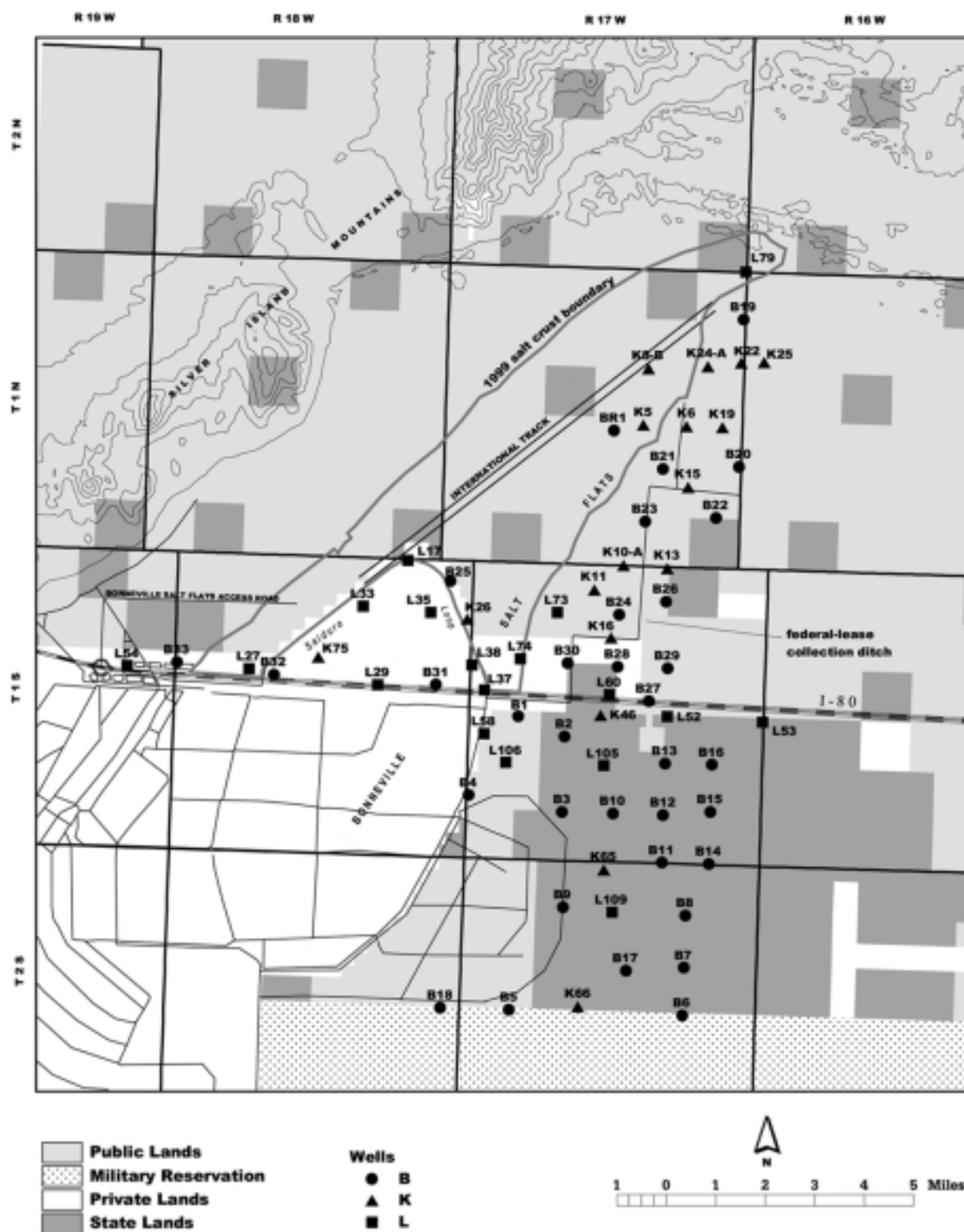
Figure 5. *Locations of 1981 USGS (Conservation Division) monitoring-well and auger-hole samples. Well sites are identified by "K" prefixes, and auger holes are identified by "B" and "L" prefixes.*
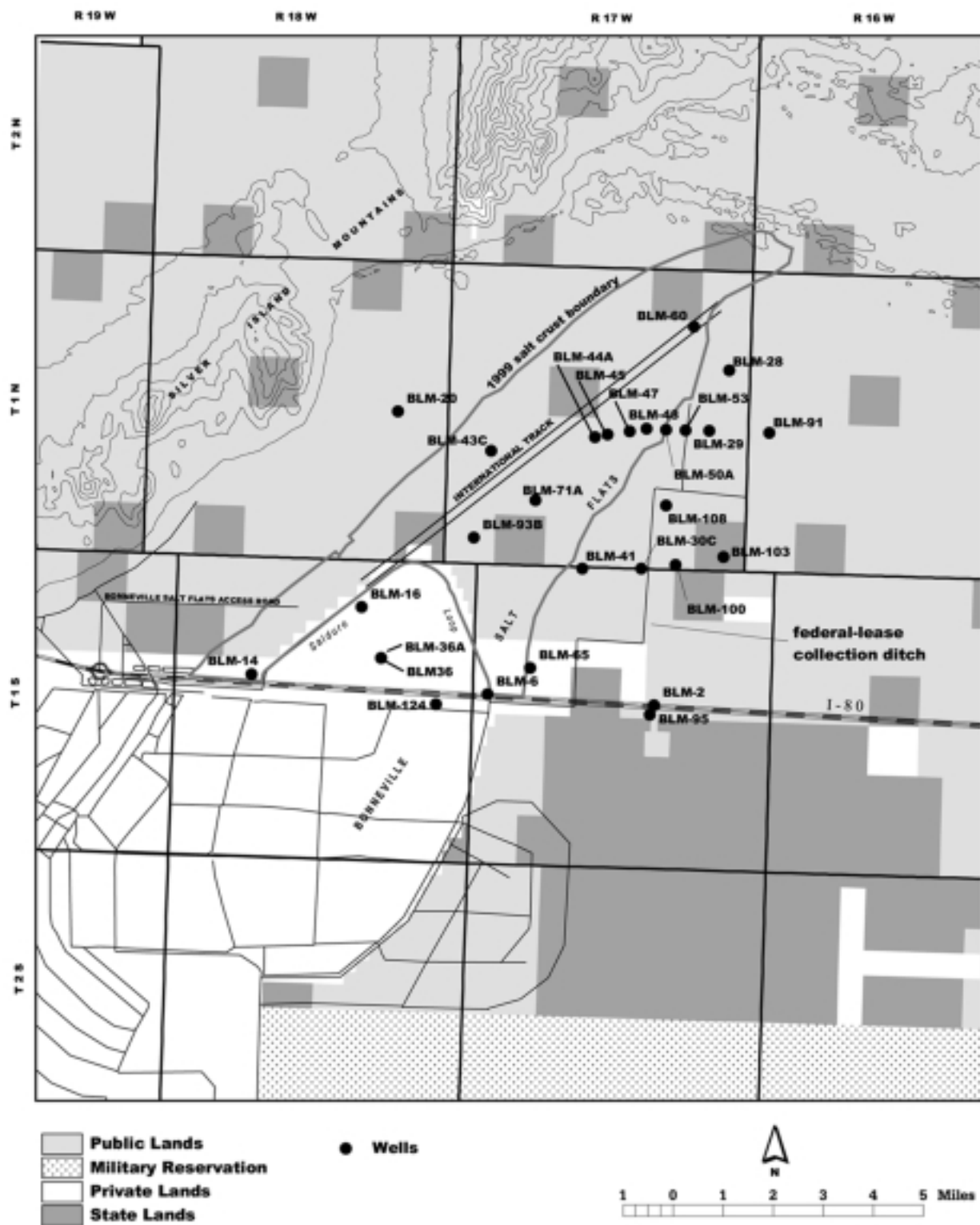
Figure 6. *Monitoring-well sample locations for 26 wells sampled by USGS in 1992-93 (Mason and others, 1995, p. 46-50). Nine of these monitoring wells were also sampled by BLM during its 1994-97 sampling period.*
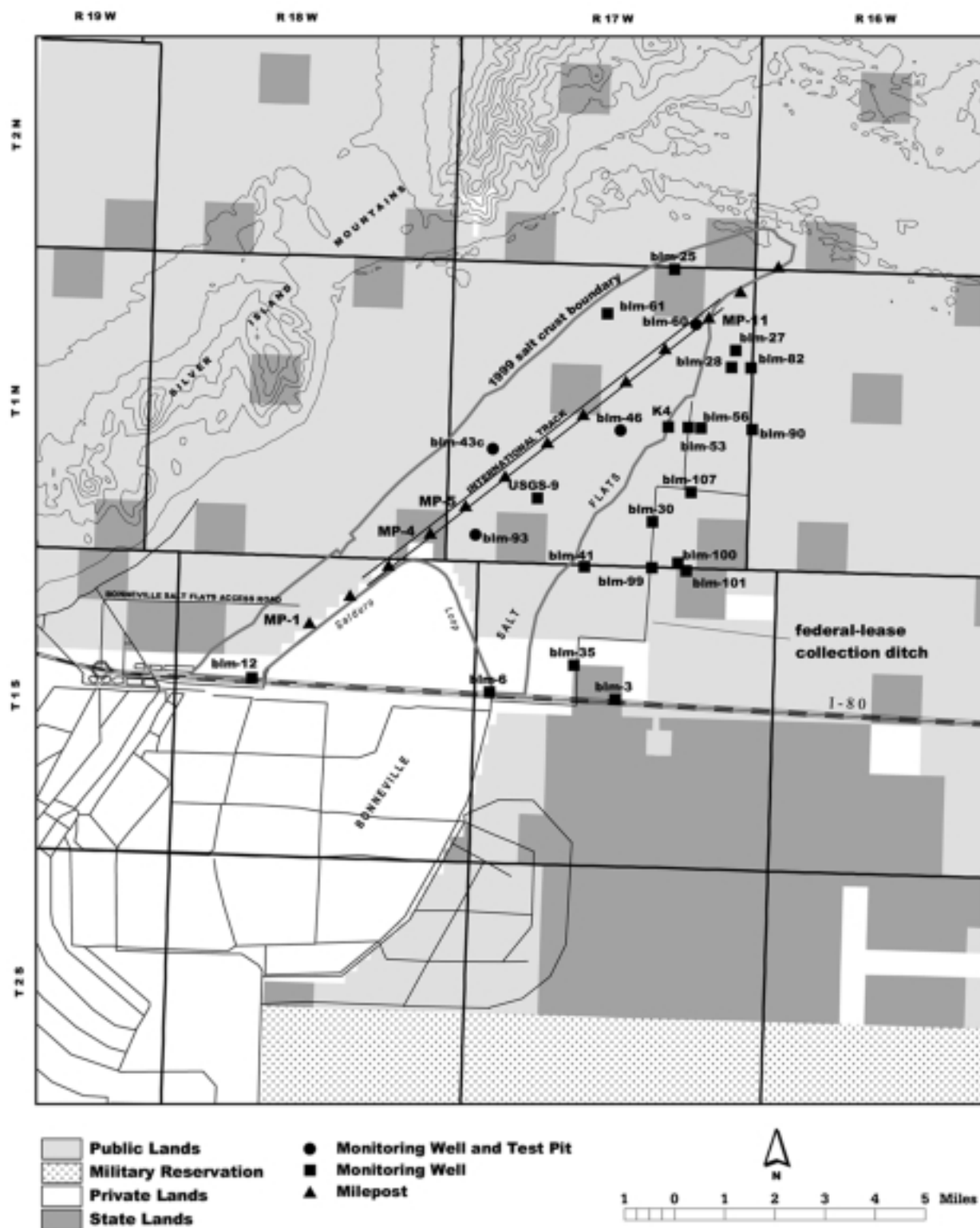
Figure 7. *Location map showing positions of 27 monitoring-well and test-pit locations with respect to the 1999 salt-crust boundary.*

resulted in yearly variation of the sample suite (table 1).

BSF shallow-brine aquifer samples were collected from the selected monitoring wells with a 3-foot-long, 1.6-inch O.D. polyethylene bailer, and stored in 8-ounce (237 mL), low-density polyethylene sample bottles. Density measurements and chemical analysis for specific ions were determined by Chemical and Mineralogical Services (CMS), Salt Lake City, UT. Sodium and potassium concentrations were determined using an Instrumentation Laboratories Model 343 flame photometer. Calcium and magnesium were determined by disodium ethylenediaminetetraacetie acid (EDTA) titration (EPA methods 311C and 314B). Sulfate (SO_4) was determined gravimetrically by barium chloride precipitation (EPA method 426A), and chloride was determined by silver nitrate titration using the Mohr method. Sample densities were determined with a density meter and verified with a hydrometer (EPA method 210B). Total dissolved solids (TDS) were calculated by summation of cation and anion concentrations. To check the accuracy of the analyses, the mole-balance method described by Sturm and others (1980, p. 175) was used.

Chemical analyses of monitoring well brines, sampled during FY94, FY95, FY96, FY97, and FY2K, are listed in appendix A2. Molar concentrations were calculated from

Table 1. Summary of well depths and sampling history for 27 BSF monitoring wells.

Monitoring Well no.[1]	Well Depth feet[2]	Sample Collected and Analyzed (X)				
		FY94	**FY95**	**FY96**	**FY97**	**FY2K**
BLM-3/USGS-60	8.0	X	X	X	X	X
BLM-6/USGS-37	19.0	X	X		X	
BLM-12/USGS-28	19.0	X	X	X	X	
BLM-19/USGS-68	9.0		X			
BLM-25/USGS-1	19.0	X	X	X	X	
BLM-27	27.7*				X	X
BLM-28	25.0	X	X			
BLM-30	14.0	X		X	X	X
BLM-35/B-30	6.1*	X		X		X
BLM-41/USGS-21	18.0	X		X	X	X
BLM-43C/USGS-5	16.0	X	X	X	X	
BLM-46	9.0	X	X	X	X	
BLM-50A/K-4A	23.0	X	X	X		
BLM-50B	8.3				X	X
BLM-53/K-3	25.0	X	X	X	X	X
BLM-56	9.0					X
BLM-60/USGS-2	19.0	X	X	X	X	
BLM-61/USGS-66	5.0	X	X	X	X	
BLM-71A/USGS-9	16.0	X				
BLM-82/K-22	25.0	X	X		X	
BLM-90	10.4				X	X
BLM-93	12.0			X	X	
BLM-99	9.7	X		X	X	
BLM-100	9.9				X	
BLM-101/K-14	11.0*	X		X		
BLM-107	10.3	X		X	X	X
BLM-107A	NL				X	
n =		19	13	16	20	10

NL Not listed
* Measured
[1]From Mason and others, 1995, table 1; BLM survey number with matching alternate number (if available).
[2]Mason and others, 1995, table 2; all depths are reported unless otherwise indicated.

each of the major-ion concentrations listed for each sample (Na, Mg, K, Ca, Cl, and SO$_4$), and then averaged by sample year. Molar ratios of K/Mg, Cl/Na, and SO$_4$/Ca were then calculated from the average molar concentrations for each sample year.

Laydown Brine Sampling and Analyses

During the November-April pumping periods of FY98, FY99, and FY2K, Reilly collected brine samples daily from BP no. 3. Brine-pump hour-meter readings were recorded concurrently with sample collection. Brine density and concentration of specific ions were determined, for each sample, in Reilly's Wendover laboratory. Sodium and potassium concentrations were determined by flame photometry using an Automatic FP 1L943. Calcium plus magnesium concentrations were determined by EDTA titration using Calmagite as an endpoint indicator. Sulfate (SO$_4$) was determined gravimetrically using barium chloride precipitation. Daily sample sodium, magnesium, and potassium concentrations (g/L) were converted to their respective chloride salts, in units of weight percent and tons, based on mole balance and density. Analytical results for the FY98 and FY99 daily samples are listed in White and Wadsworth (1999, appendix 3, tables A3.1-A3.13). FY2K daily samples are in White and Wadsworth (2001).

To provide independent verification of laydown-brine quality, BLM collected triplicate samples of laydown brine from sample sites at key facility locations. These samples were collected during the November-April pumping periods of FY98, FY99, and FY2K. A total of 255 sample triplicates, comprising 85 samples, were collected during the 3-year period. Sample triplicates were identified as "A", "B", and "C", and attached to a sequential number (for example, A-1, B-1, C-1; A-2, B-2, C-2; etc.). The "A" triplicates were submitted to Reilly, "B" triplicates were retained by BLM to be analyzed by CMS (BLM's contracted analytical laboratory), and the "C" triplicates were submitted to University of Arizona, Department of Chemistry [(U of Az), STS's contracted analytical laboratory]. Laydown-sample analyses are listed in appendix A3.

The key-facility sample sites include the concrete vault at BP no. 3, and the west and east end of the laydown manifold (LDM-W and LDM-E); see figures 2 and 3. These sample sites were selected because they comprise the primary laydown-brine distribution system which directly affects the BSF. Additionally, a lag in brine travel time exists between BP no. 3 and LDM-E, and these sample sites provided easily accessible check points to more closely monitor changes in brine quality. Brine-density measurements using a CL-USA no. 458438 hydrometer were determined in the field for each sample.

CMS chemical analyses for "B" triplicates followed the protocol summarized in "Monitoring Well Sampling and Analyses." U of Az chemical analyses for "C" triplicates used the following protocol: after dilution, the samples were analyzed for sodium (Na), calcium (Ca), potassium (K), and magnesium (Mg), using a Thermo Jarrell Ash IRIS-HR inductively coupled plasma (ICP) emission spectrometer; the spectrometer was calibrated using solutions made from pure salts. Because U of Az did not report chloride and sulfate (Cl and SO$_4$) concentrations, CMS values for Cl and SO$_4$ from

matching "B" triplicates were used to estimate mole balance for each "C" triplicate sample.

Laydown Brine Flow-Rate Measurement

Laydown-brine flow rates were measured from two locations at BP no. 3: 1) a hand-held Swaffer Instruments Inc. Current/Flow Velocity flowmeter 2100-LX was used to measure flow where the active-pump discharges inside the concrete brine-storage vault, and 2) a Dynasonics Flowmeter model M3-901 connected to a Campbell Scientific CR10X datalogger continuously monitored flow from the active-pump discharge pipe at a point midway between the pump and the concrete vault (see figure 3).

A flow-rate range was measured with the 2100-LX in April 1998, and averaged 6,688 gpm. During the FY99 and FY2K pumping periods, an additional 23 measurements with the 2100-LX flowmeter averaged 6,685 gpm, which is in good agreement with the initial April 1998 average.

A recent compilation of Dynasonics M3-901 flow-rate measurements, taken over a 77-day period (December 15, 1999 through 29 February 2000), produced an average flow rate of 6,600 gpm, which is in reasonable agreement with the 2100-LX average of 6,685 gpm. However, Dynasonics flow rates were typically lower than 2100-LX flow rates. Because the Dynasonics was calibrated with 2100-LX-measured flow rates, the Dynasonics average will be considered an estimate until differences between both flow-meter values can be reconciled. Consequently, in this paper, the average 2100-LX flow-meter measurements are being used to calculate NaCl tonnages. For conversion of gallons of laydown brine to tons of NaCl, see White and Wadsworth (1999, appendix 3, equations 1-3).

Geochemical Modeling of Laydown and BSF Shallow-Aquifer Brine Mixing

A transient pond usually forms in low areas of BSF from November through March or April (Lines, 1979, p. 11, 51, 85-86). This pond is a combination of seasonal meteoric precipitation and shallow-brine aquifer ponding on the BSF surface during the winter months (Mason and Kipp, 1998, p. 65-66). Because the laydown-pumping cycle is from November through April, laydown brines mix with the transient pond, and ultimately with the shallow-brine aquifer.

Geochemical modeling was performed to determine if this mixing has any effect on the chemistry of shallow-brine aquifer and salt-crust composition, and to examine the fate of laydown-brine NaCl after being mixed with the water of the shallow-brine aquifer. A temperature-dependent chemical equilibrium model (TEQUIL) was used to: 1) calculate the equilibrium composition of six years of shallow-brine aquifer samples and six brine-mixing simulations, and 2) predict which salts would precipitate from these simulations at each step of a 45-step evaporation routine.

To assess the impact of mixing laydown brine with the shallow-brine aquifer, TEQUIL was used in the following applications:

• Determine if chemical differences exist among six different years of shallow-brine aquifer samples collected prior to the Laydown Project, and classify the annual

sample suites by their predicted evaporative-mineral assemblages.

• Use the TEQUIL-predicted mineral assemblages to help classify any differences between the shallow-aquifer brine and laydown brine.

• Predict the mineral assemblages that would result from mixing laydown brine with shallow-aquifer brine (four mixing simulations).

• Predict the mineral assemblages that would result from mixing transient-pond brine with rainwater, and with shallow-aquifer brine (two mixing simulations).

• Identify the fate of laydown NaCl after mixing with the shallow-brine aquifer.

• Evaluate TEQUIL's integrity by simulating the solar-pond conditions used in potash production, and comparing modeled output with published data.

Salt-Crust Thickness Measurements

Since 1994, BLM has excavated 12 test pits and drilled 11 auger holes in the BSF salt crust. The purpose of the test pits was to: 1) identify the stratigraphic components of the salt crust, and 2) determine if a recognizable geologic datum exists that could be used to measure potential changes in salt-crust thickness after each 6-month pumping period. The auger holes were drilled to record the salt-crust thickness at specific locations. Two previous salt-crust thickness studies were conducted by the Utah State Department of Highways (UDOT) and BLM between 1960 and 1988 (McMillan, 1974; Brooks, 1991). UDOT and BLM each augered more than 100 holes in the salt crust during their respective studies. Salt-crust thickness differences between the UDOT and 1988 BLM studies are summarized in White and Wadsworth (1999, p. 36-37). Because the 1988 BLM auger-hole locations were surveyed (Brooks, 1991, p. 4), and their salt-crust thicknesses were the most recent historical measurements, 1988 thicknesses were compared with 1998 and 2000 BLM measurements to see if thickness changes could be observed. The locations of 1998 and 2000 auger holes were plotted on a computer-generated isopach map of the 1988 salt-crust thickness measurements. The 1988 isopach map was generated by the Radian Corporation program CPS/PC v. 4.2. Salt-crust thicknesses, corresponding to the 1998 and 2,000 auger-hole locations, were read directly from the 1988 isopach map through the computer program (J. F. Kohler, Geologist, BLM Utah office, personal communication, December 2000).

During a three-year period prior to the start of the Laydown Project (September 1994 and 1995, and October 1997), BLM excavated a total of 10 test pits along a 7-mile segment of the International Track, within 1 mile of the track centerline (see figure 7). This segment extended from mile post no. 4 to mile post no. 11 (original 1960 and 1974 UDOT locations). The 10 pits were located adjacent to six, reference BSF monitoring wells (BLM-42a, BLM-43c, BLM-46, BLM-60/USGS-2, BLM-93, and BLM-71A/USGS-9). The first few pits were excavated with a variety of hand tools (screwdriver and geologic pick, J. F. Kohler, Geologist, BLM

Utah office, personal communication, September 1997). A chain saw was much more efficient in excavating the later pits. Successive salt and gypsum strata comprising the salt crust exposed at each pit site were described and their respective thicknesses measured.

Since the start of the Laydown Project (November 1997), BLM excavated two additional test pits and drilled nine auger holes to determine if measurable changes in salt-crust strata thickness had occurred. The two additional pits were located adjacent to the BLM-93 monitoring well. A chain saw was used to cut pits an average of 24 inches square and about 14 inches deep. The first test pit was excavated in August 1998, approximately 95 feet NW of BLM-93 (see figure 7). The second test pit was excavated in July 2000, within 10 feet of the August 1998 pit. Total salt-crust thickness at the July 2000 test-pit site was determined by drilling an auger hole adjacent to the pit. Salt and gypsum strata exposed in the two pits were described and their thicknesses measured.

During 1998-1999, five auger holes were drilled along the International Track with a 4.0-inch outside diameter soil auger. Auger-hole locations were determined by a Trimble ScoutMaster Global Positioning System receiver. Salt-crust strata were described and their thicknesses recorded. Total salt-crust thickness for each hole was determined by identifying the salt-crust/carbonate-mud interface in the recovered auger core, and by matching it with the corresponding auger-drilling depth.

Four additional auger holes were drilled in July and October 2000, and located near BLM-43C, BLM-46, BLM-60, and BLM-93. Each hole was started with an "Earthquake" model 8900E, 4-inch diameter motorized auger, and completed with an AMS 4.625-inch O.D. mud auger. Respective drilling depths for each tool were recorded. Each hole was completed with the mud auger so that the salt-crust/carbonate-mud interface could be visually verified in the recovered core. Matching the confirmed salt-crust/carbonate-mud interface with recorded drilling depths provided more precise salt-crust thickness measurements. Successive salt-crust strata, exposed in the five auger holes, were described and their thicknesses measured. Because ponded water was present on BSF, test pits were not excavated.

Salt-Crust Areal Extent Measurements

Landsat 5 Thematic Mapper images (Jensen, 1996, p. 37-44) for September 8, 1997, August 28, 1998, and October 8, 1999 were used to estimate the areal extent of BSF salt crust one month prior to, and during the first two years of, the Laydown Project. Because the imagery was selected and purchased after its flight date, field checking to confirm the salt-crust boundaries on those dates was not possible. A qualitative estimate of the salt-crust/mud-flat boundary location for each of the three years was determined by examining images produced by a color composite and selected individual bands. The color composite was made up of bands 2, 3, and 4 (Jensen, 1996, p. 40), and most closely approximated the color of the natural ground surface. Bands 2, 3, and 4 were also examined individually.

All three years of imagery showed that the salt-crust's north-west boundary remained relatively static, while the east boundary, adjacent to the Federal lease collection ditch,

showed visible change during the 1997-1999 period.

The color composite images for each of the three years were examined first to estimate the location of the east salt-crust boundary. Areas of known salt crust and mudflat were compared with what appeared to be the east salt-crust/mudflat boundary, and a tentative east boundary was drawn. The boundaries for each delimited area were then superimposed on the corresponding Landsat scene, displayed as a single band gray-scale image (either band 3 or 4). The tentative east boundary from the color composite was compared with the single-band gray-scale image. If an eastern boundary suggested by the single band gray-scale image was in reasonable agreement with the boundary suggested by the color-composite image, then that boundary was used in the area calculations. Reasonable agreement between eastern boundaries from the color-composite and single-band gray-scale images was achieved for all three years of imagery.

Because I-80 and the Salduro Loop berm formed a consistent southern boundary for the study area, and the northwest boundary remained relatively static, the tentative east boundary was connected with the southern and northwestern boundaries to delimit the salt-crust area for each year. The area inside the Salduro Loop was not included in the measurements.

RESULTS AND DISCUSSION

Laydown brine has been delivered to BSF for the past three years with the objective of adding salt to the salt crust. The laydown brine was discharged to the salt crust from November through April where it mixed with the winter transient pond. Depending upon yearly weather conditions, this pond can cover most of the BSF playa surface (Mason and Kipp, 1998, p. 33). The transient pond typically begins to form on the surface of the salt crust in October or November when temperatures cool, evaporation decreases, and discharge from the shallow-brine aquifer pools at the land surface (Lines, 1979, p. 11, 51, 85-86; Mason and Kipp, 1998, p. 65-66). Because of its source and location (mainly on the salt crust), the transient pond is hydrologically connected with the shallow-brine aquifer.

Meteoric precipitation also contributes to formation of the transient pond. Rainwater from fall and winter storms falls on the developing pond and playa surface where it dissolves halite from the salt crust until the fresh water is saturated, and ultimately mixes with the transient pond by wind action (Mason and Kipp, 1998, p. 55). The transient pond eventually dissipates as evaporation from the pond increases during late spring and early summer. As the transient pond begins to shrink from evaporation, it becomes saturated with respect to NaCl. Eventually, the pond disappears when evaporation reaches its peak during the summer. The extent of mineral precipitation and the type of mineral species precipitated are governed by the chemical composition of the transient pond and the amount and duration of evaporation.

Although the engineering design estimated that up to 0.4 inches of NaCl would be added to the salt crust each year (Bingham, 1991, p. 2), the effects of adding laydown brine to the transient pond were unknown. The results that are presented focus on the following questions regarding the influence of adding laydown brine to the transient pond:

- How much dissolved salt was delivered to BSF by the Laydown Project?

- How much salt was added to the salt crust?

- Does shallow-aquifer brine chemistry vary historically, and how does it compare with laydown brine chemistry?

- How does the composition of salt, precipitated as a result of the Laydown Project, compare with that of pre-laydown salt crust?

- How much dissolved laydown salt may be assimilated into the shallow-brine aquifer?

- Has the composition of the minerals precipitated from the shallow-brine aquifer changed as a result of the Laydown Project?

Progress of Salt-Crust Restoration

Tons of Salt Delivered to BSF

After three years of operation, the Laydown Project has delivered 4.5 billion gallons of brine containing 4.6 million tons of NaCl to BSF (table 2). This amount exceeds the expected tonnage at this stage of the project - the feasibility study (Bingham, 1991, p. 2) anticipated yearly tonnages of up to 1.5 million tons.

Because of start-up problems during the first year of the project, 825,206 tons of NaCl, or about half of the anticipated tonnage, was produced in FY98. However, the FY98 tonnage nearly matched the 850,000 tons of annual salt loss estimated by the USGS (Mason and Kipp, 1999, p. 93). The lower than expected FY98 tonnage was mainly due to the mechanical failure of BW no. 1 that caused a 37-day down period from November 15 to December 22, 1997.

An additional delay, totaling 27 days in 1998, occurred because of deteriorating brine quality in primary pond no. 4 (PP no. 4). Brine densities for December and January were 1.080 and 1.074 g/mL, respectively (table 3), and corresponding salt (NaCl) tonnages delivered to BSF were 30,739 and 80,359 tons (appendix A4). Brine pumping was discontinued from January 28 through February 16, 1998 while the system was modified to increase salt dissolution (see White and Wadsworth, 1999, p. 22-23). As a result, average brine densities increased from respective values of 1.080 and 1.074 g/mL in December and January, to respective values of 1.178 and 1.148 g/mL in late February and March (table 3). February and March NaCl tonnages increased to 129,792 and 278,446 tons, respectively (appendix A4). When brine quality dropped below acceptable limits in April, Reilly again closed the discharge gate at the southeast corner of PP no. 4 for a seven-day period (April 9-15, 1998) until brine quality improved.

During FY99, the second year of the Salt-Laydown Project produced 1.965 million tons of NaCl (table 2). This tonnage was 1.3 times the anticipated tonnage (1.5 million tons per year) and 2.3 times the USGS estimated annual salt loss. Additionally, the FY99 salt tonnage was 2.4 times the total salt tonnage delivered to BSF during FY98. The marked increase in FY99 salt tonnage was due to improvements made to the laydown facility during the summer and fall of

1998. Improvements included doubling the time required to fill PP no. 4 (from 30 to 60 days), and ripping the pond's salt-crust surface. FY99 brine-density values (table 3) also reflected effects of the facility improvements; average densities approached NaCl saturation and had a narrow range of 1.183 to 1.194 g/mL for the 6-month period.

Effects of the laydown facility improvements continued and are reflected in FY2K production figures. The third year of the project produced 1.833 million tons of NaCl, or 1.2 times anticipated tonnage and about 2.2 times the USGS estimated annual salt loss. Although brine density values decreased slightly in January and February, brine density was increased in March by bulldozer ripping the salt-crust surface of PP no. 4 (table 3).

Accuracy of Chemical Analyses

Sixty-nine of the 85 samples of laydown brine, collected during the first three years of the Laydown Project, were subjected to interlaboratory analyses by Reilly, CMS, and U of Az. Agreement for NaCl analyses among the laboratories was very good, with replicate analyses being within about 6

percent of the mean value (appendix A5).

The interlaboratory NaCl analyses of laydown-sample triplicates collected by BLM during FY98 through FY2K are summarized in table 4. Reilly and CMS average analyses of the FY2K samples were in excellent agreement (0 percent difference), as were their respective average analyses of the FY99 samples (2 percent difference from the mean). Reilly, CMS, and U of Az average analyses of the FY98A samples were also in excellent agreement (2.2 percent difference from the mean), while good agreement was observed between Reilly, CMS, and U of Az average analyses of the FY98B samples (5.7 percent difference from the mean).

Amount of Salt Added to the Salt Crust

Area - Based on measurements from Landsat 5 imagery, the areal extent of the salt crust increased by about 5 square miles or 17 percent during a two-year period (September 1997 to October 1999). BSF salt-crust areas measured from fall 1997, 1998, and 1999 Landsat 5 scenes were approximately 26, 29, and 31 square miles, respectively. Figure 8 shows the 1997, 1998, and 1999 salt-crust boundaries super-

Table 2. FY98-2K totals of laydown-NaCl tonnage, acre feet, gallons, and pump hours.

TOTALS	NaCl,	Pumped Brine		Hours Pumped Per Year (Nov.-Apr.)		
	Tons (dry)	Acre Feet	Gallons	Maximum Possible	Actually Pumped	% of Possible
FY98	825,206	3,161	1,030,008,750	4,344	2,567	59.1
FY99	1,965,068	5,335	1,738,215,000	4,344	4,332	99.7
FY2K	1,833,074	5,345	1,741,425,000	4,368	4,340	99.4
FY98-2K	4,623,348	13,841	4,509,648,750	13,056	11,239	86.1

Table 3. Average monthly laydown-brine-density values (expressed in g/mL) for November through April during FY98-FY2K[1].

MONTH	NOV	DEC	JAN	FEB	MAR	APR
FY98	1.161	1.080	1.074	1.178	1.148	1.133
FY99	1.194	1.192	1.183	1.187	1.186	1.189
FY2K	1.187	1.178	1.152	1.145	1.178	1.202

[1]Density values based on daily brine-sample measurements conducted in Reilly's Wendover laboratory.

Table 4. Three years of laydown-brine NaCl analyses; all samples collected by BLM and analyzed by Reilly, CMS, and U of Az; average Na and Cl concentrations converted to chloride-salt equivalents (expressed as wt percent in solution).

SAMPLES	n	Reilly	CMS	U of Az	mean
FY2K	29	21.62	21.62	ND	21.62
FY99	23	21.97	21.13	ND	21.55
FY98A	9	7.59	7.39	7.69	7.56
FY98B	8	17.49	16.05	16.12	16.55
ND Not determined					

1997 Salt Boundary
1998 Salt Boundary
1999 Salt Boundary
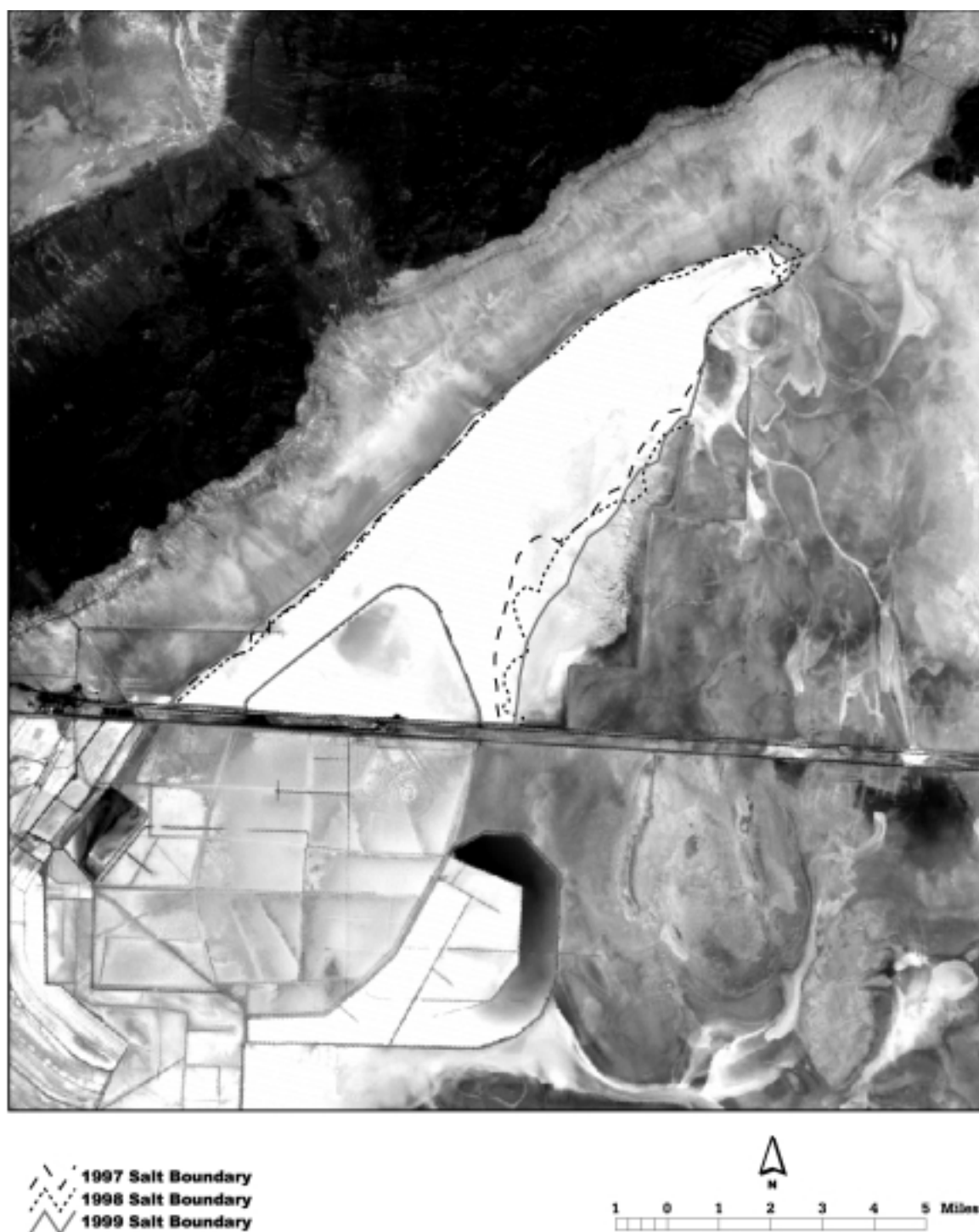
Figure 8. *1999 Landsat 5 image showing progressive increase in salt-crust area from September1997 through October 1999.*

imposed on the 1999 Landsat 5 image of BSF. The 1999 image was selected to show the compared areas because its salt-crust areal extent was the largest of the three years measured.

Because 2.8 million tons of NaCl had been delivered to BSF between November 1997 and October 1999 (FY98 and FY99 laydown tonnage - see table 2), estimates of NaCl tonnage contained in the 5-square mile area were made for comparison with the amount delivered during those two years.

The estimated tonnage contained in the new area of salt crust was based on the following:

• Reported halite densities (dry) ranged from 79.4 to 109.8 pounds per cubic foot (Brent Bingham, 1998, Bingham Engineering, personal communication; Mason and Kipp, 1998, p. 54).
• New salt-crust thickness was estimated to range from 0.25 to 1.0 inches (from preliminary thickness measurements taken in June 1998).

Based on these parameters, new salt-crust tonnages for the 5-square mile area ranged from about 0.12 to 0.64 million tons. The 0.64 million tons represents about 23 percent of the 2.8 million tons of NaCl delivered by the Laydown Project during FY98 and FY99. To contain 2.8 million tons of salt, the 5-square mile area of new salt crust would have to average more than 4 inches thick. Salt-crust thickness studies, and geochemical modeling of the effects of mixing laydown brine with the shallow-aquifer brine (described in the following sections), suggest that the remainder of the laydown salt tonnage not included in the 5-square mile area was distributed between the main body of the salt crust (26 square miles in 1997) and the shallow-brine aquifer.

Surface Stratum Thickness - Based on the salt-replenishment feasibility study by Bingham (1991, p. 2), it was anticipated that about 0.4 inches per year of salt thickness would be added to the surface of the salt crust. To quantify this addition, BLM evaluated two methods for measuring changes in thickness. The first method was to measure elevation differences between the salt-crust surface and the surveyed top-of-casing elevations from selected monitoring wells located on the salt crust. However, the combination of uneven salt-crust surfaces and the cratering of the salt-crust surface surrounding each casing (caused by rainwater running down the sides of the casing) made thickness-change measurements highly subjective. For this reason, this method was not used.

The second method was to use a distinct salt crust stratum as a horizon from which to reference all thickness measurements. Such a stratum was identified, based on 10 test pits excavated by the BLM between 1994 and 1997. These pits were adjacent to six reference BSF monitoring wells (BLM-42a, BLM-43c, BLM-46, BLM-60/USGS-2, BLM-93, and USGS-9) located along the trend of the International Track (see figure 7). Examination of these pits indicated that five distinct strata comprised the salt crust and were consistent in sequence and composition from pit to pit (table 5; Kohler, 1995, and Kohler and White, 1997).

An uncemented gypsum stratum, ranging from 0.5 to 1.2 inches thick, was always the first stratum underneath the dense-cemented halite stratum (the bedded halite that makes up the surface of the salt crust). The upper surface of the gypsum stratum was used as the thickness-measuring datum for all salt-crust thickness measurements reported in this paper. Note that the sequence contains two different uncemented gypsum strata, and that the first (top) gypsum stratum is the measurement datum. More detailed descriptions of each salt-crust strata are in appendix 6.

Thickness measurements for several of the strata were complicated by the presence of undulating top and bottom surfaces. The dense-cemented halite stratum typically had an undulating bottom surface, and the cemented-coarse-porous halite stratum had undulating top and bottom surfaces. To account for the variable thickness caused by these surfaces, three measurements were usually taken of each stratum (one in the middle, and one at each end of the stratum length exposed in the test pit). Based on these three measurements, thicknesses for each stratum were usually presented as a range of values. However, to facilitate stratum thickness comparisons from year to year, the range of thickness values for each stratum were averaged.

Two additional test pits and nine auger holes were exca-

Table 5. Salt-crust strata sequence and thickness ranges from 10 BLM test pits (Kohler, 1995, and Kohler and White, 1997).

STRATA	Thickness, inches
Dense-cemented halite (surface bed of the salt crust)	1.3 to 2.9
1st uncemented gypsum mixed with carbonate clay	0.5 to 1.2
Cemented-coarse-porous halite	1.4 to 7.7
2nd uncemented gypsum mixed with carbonate clay	0.4 to 1.8
Uncemented-coarse halite	18.0 to 24.0[1]
Carbonate clay	ND

ND Not determined

[1]Thickness range is based on one test pit which was excavated to the salt/mud interface.

vated during 1998-2000 to determine variations in the thickness of the dense-cemented halite stratum as well as other strata. These excavations provided salt-crust, stratum-thickness comparisons with four of the 10 test pits excavated during the 1994-1997 period, and a limited comparison of total salt-crust thickness with 1988 thickness measurements by Brooks (1991). Tables 6 and 7 list stratum thickness comparisons at BLM-93, BLM-43c, BLM-46, and BLM-60. The following observations can be made from these comparisons:

• Dense-cemented halite stratum thickness increased at BLM-93 by 0.4 to 0.5 inches (an approximate 20-25 percent increase), and decreased by 0.9 to 1.3 inches (an average decrease of about 35 percent) at BLM-43c, BLM-46, and BLM-60.

• Cemented-coarse-porous halite stratum thicknesses increased by 0.4 and 2.2 inches (about a 15 and 120 percent increase) at BLM-43c and BLM-60 sites when dense-cemented halite stratum thicknesses decreased at the same locations.

It was originally thought that annual measurements of the surface stratum (dense-cemented halite) would show a gradual thickness increase from salt addition by the Laydown Project (0.4 inches per year). However, based on thickness comparisons in tables 6 and 7, dense-cemented halite stratum thicknesses increased at BLM-93, but decreased at BLM-43c, BLM-46, and BLM-60. These thickness decreases occurred, despite an addition of 4.6 million tons of NaCl salt to BSF during the first 3 years of the Laydown Project. Several factors may have contributed to the measured decrease in dense-cemented halite stratum thickness:

• Annual variations in weather.

• Laydown salt contributions to the shallow-brine aquifer.

• Laydown salt contributions to increased salt-crust area.

• Laydown salt contributions to other salt-crust strata.

Annual variations in weather can produce changes in salt-crust strata thicknesses. The thickness of the dense-cemented halite stratum would tend to decrease if an unusually wet winter were followed by a cool summer (when rainfall is high and evaporation is low due to colder temperatures). An unusually wet winter could increase dissolution of the dense-cemented halite stratum thickness because of increased rainfall on the surfaces of the salt-crust and the transient pond. For example, Mason and Kipp (1998, p. 55) estimated 10 to 14 million tons of salt were dissolved from the salt crust just north of I-80 during the winter of 1993. This was due to greater than normal precipitation in January, and unseasonably cool temperatures in January and February. During a cool summer, less evaporation could reduce replenishment of the dense-cemented halite stratum. Conversely, if a dry winter were followed by a hot dry summer the dense-cemented halite stratum thickness would tend to increase. A dry winter would lead to less salt-crust dissolution. A dry summer would tend to increase evaporation of the shrinking transient pond and discharging shallow-aquifer brine; consequently, salt precipitation, and salt-crust thickness would be increased. Annual thickness changes in the dense-cemented halite stratum, due to changes in annual weather conditions, would make it difficult to measure the thickness added to the surface stratum by the Laydown Project, regardless of the measurement method. For example, a decrease in thickness of 0.5 inches (or more) in the dense-cemented halite stratum from weather-related conditions could easily mask the annual 0.4-inch increase in salt-crust thickness predicted by the Laydown Project design. Depending upon the amount of halite dissolved from the surface stratum, an apparent thinning of the dense-cemented halite stratum could occur during unseasonably wet years in spite of increased salt tonnage added to BSF by the Laydown Project.

TEQUIL modeling calculations indicate that between 17 and 25 million tons of laydown-brine NaCl could be assimilated into the shallow brine aquifer (see "Fate of laydown-brine NaCl when mixed with the shallow-brine aquifer"). Whereas this salt would eventually be incorporated into the salt crust as halite, there may be a lag time between the period of laydown-brine delivery and this incorporation. Conse-quently the effects of this salt addition would not be measured until some time in the future.

As was previously discussed, laydown NaCl mass added to the salt crust can manifest itself through increases in thickness or increases in area. From September 1997 to October 1999 the area of the BSF increased by five square miles. This area could contain as much as 0.6 million tons of laydown NaCl.

Laydown NaCl mass added to the salt crust may also be added to the cemented-coarse-porous halite, and the uncemented-coarse halite strata (tables 6, 7). Data from test pits adjacent to monitoring well BLM-93, and those adjacent to monitoring wells BLM-43C and BLM-60, can be used to assess changes in the thickness of the cemented-coarse-porous halite stratum. All three sites indicate substantial increases in the thickness of the cemented-coarse-porous halite stratum measured in 2000 (tables 6, 7). It is conceivable that some of this increase is the result of the Laydown Project. Because the subsurface salt-crust strata (cemented-coarse-porous halite or uncemented-coarse halite strata) are saturated by the shallow-brine aquifer, their observed thickness changes may be due to alternating halite crystal growth and dissolution:

• Existing halite crystals could act as nucleating sites for additional crystal growth, especially during the summer when evaporation of shallow-brine aquifer could cause a concentration gradient in the brine.

• Conversely, a wetter than normal winter, such as 1993 (Mason and Kipp, 1998, pp 26, 55), would lower shallow-aquifer brine densities (that is, 1.186 gm/cm^3 for 1993 vs 1.194 gm/cm^3 for 1992 - see table 9) which could result in some partial halite-crystal dissolution.

Total Salt-Crust Thickness - During October 1998 and September 1999, five auger holes (MB-1 - MB-3, MB-6, and MB-7) were drilled by the BLM in the salt crust adjacent to the International Track between mile posts no. 1 and no. 5 (see figure 7). Total salt-crust thicknesses measured from these five auger holes, and from four holes drilled in 2000 (adjacent to BLM-43c, BLM-46, BLM-60, and BLM-93),

Table 6. Salt-crust strata sequence and thickness ranges from 5 BLM test pits adjacent to monitoring well BLM-93.

STRATA	Strata Thickness, inches				
	1994 (pit 1a)[1]	1995 (pit 1b)[1]	1997 (pit 1c)	1998 (pit 1d)	2000 (pit 1e)
Dense-cemented halite	1.8	1.9	1.9	2.25 to 2.5	1.5 to 3.0
1st uncemented gypsum mixed with carbonate clay	1.0	0.7	0.6	1.0 to 1.25	1.0
Cemented-coarse-porous halite	2.9	2.4	2.0 to 3.5	1.0 to 2.25	4.5 to 7.5
2nd uncemented gypsum mixed with carbonate clay	0.6	0.6	0.5 to 0.75	0.75 to 2.25	0.0 to 1.0
Uncemented-coarse halite	ND	ND	ND	ND	29.0[2]

ND Not determined

[1]Kohler, 1995 unpublished field notes.

[2]Total thickness of uncemented-coarse salt (depth to salt/mud interface measured).

Table 7. Strata-thickness comparisons between three October 2000 auger holes and three 1994 test pits located adjacent to BLM-43c, BLM-46 and BLM-60.

STRATA	STRATA THICKNESS, INCHES					
	BLM-43c		BLM-46		BLM-60	
	1994	2000	1994	2000	1994	2000
Dense-cemented halite	2.9	2.0	3.1	2.0 to 2.25	2.8	1.5
1st uncemented gypsum	0.8	1.0	0.8	0.5	1.0	1.0
Cemented-coarse-porous halite	2.6	3.0	ND	NP	1.8	4.0
2nd uncemented gypsum	ND	NP	-	NP	0.5	13.0[1]
Uncemented-coarse halite	-	25.8	-	21.25	ND	-

ND Not determined
NP Not present
[1]Total depth of salt crust measured.

were compared with 1988 total salt-crust thicknesses measured by Brooks (1991) near the same locations. A slight decrease in thickness from 1988 to 1998-2000 was observed for seven of the nine locations. One location (MB-7) showed a slight increase (+ 0.2 feet). With the exception of BLM-93 (which showed a decrease of 0.4 feet), thickness differences were from 0 to 0.2 feet, and were within the margin of measurement error reported by Kohler (1995).

Brooks (1991, p. 3) measured 1988 total salt-crust thicknesses from each auger hole using a method similar to that used by UDOT, and reported difficulty in replicating measurements within the same hole. A hook mounted at the base of a 1-inch diameter, 5-foot long pole was dragged up along the auger-hole wall from the bottom of the hole to the surface of the salt crust. The interface between the salt crust and the underlying carbonate mud was indentified by catching the hook on the underside of the more resistant of the two surfaces that comprise the interface. The distance from interface to salt-crust was measured by reading the footage increment on the pole where it intersected the salt-crust surface. Kohler (1995) also attempted to replicate total salt-crust thickness measurements within the same hole using the USDH method, and reported thickness-measurement differences of ± 0.1 foot.

Although table 8 summarizes thickness changes over a 10 to 12-year period, only the most recent three of the 12 years would have been affected by the Laydown Project. Additionally, this preliminary comparison is based on a small population of data from nine drill-hole locations. To more accurately assess effects of the Laydown Project on total salt-crust thickness, thickness measurements from a larger population of drill holes need to be collected on a yearly schedule.

This assessment could be accomplished by drilling the same number of holes each year for at least a five-year period. The 14 transect lines Brooks (1991, figure 4) established in 1988 could be used to locate the holes. These transect lines were oriented perpendicular to the trend of the International Track and spaced on 1-mile centers. From three to five holes per transect could be drilled close to the same locations each year. This would provide yearly thickness measure-

Table 8. Comparison of salt-crust thickness measurements in nine auger holes drilled in 1998-2000 with correlative 1988 thicknesses.

Auger Hole no.	1988[1] Thickness, ft.	1998-2000[2] Thickness, ft.
MB-1	1.2	1.0
MB-2	1.0	1.0
MB-3	1.7	1.6
MB-6	1.9	1.8
MB-7	2.8	3.0
BLM-43c	2.8	2.7
BLM-46	2.2	2.0
BLM-60	1.7	1.6
BLM-93	3.9	3.5

[1]Brooks, 1991
[2] MB holes measured in 1998, and BLM-43c, etc., measured in 2000.

ments from 42 to 70 holes. With this larger population of measurements being collected annually over a 5-year period, a trend in total salt-crust thickness change could be established, and the influence of the Laydown Project on that thickness change could be assessed with greater confidence.

Brine Composition

Comparison of 1994-2000 Shallow-Aquifer Brine Samples with Historical Data

Five years of recent BLM samples of shallow-aquifer brine were compared with 186 USGS samples that were collected over a 17-year period (table 9). Sodium and chloride ions dominated both groups of samples. Sodium made up about 91 percent of cation content, and chloride made up 97 percent of anion content in both BLM and USGS samples. Magnesium and potassium jointly made up about 8 percent

Table 9. Comparison of recent (BLM) samples with historic (USGS) samples of the BSF shallow-aquifer brine (samples usually collected during August and September unless otherwise indicated).

SAMPLE SUITE	n	Density	Average Major Ion Concentrations, moles/L							Avg Mole Balance[1]
			Na	Mg	K	Ca	Cl	SO_4	TDS	
BLM:										
FY2K	10	1.173	3.74	0.102	0.110	0.033	4.09	0.051	244	0.003183
FY97	20	1.185	3.95	0.109	0.134	0.028	4.24	0.058	256	0.001462
FY96	16	1.182	4.11	0.140	0.155	0.021	4.56	0.051	282	0.003822
FY95	13	1.196	4.47	0.189	0.152	0.026	4.71	0.052	286	0.010115
FY94	19	1.192	4.47	0.224	0.162	0.022	5.00	0.055	297	0.002707
USGS:										
FY93	20	1.181	4.31	0.154	0.139	0.028	4.37	0.060	297	0.013832
FY92	26	1.185	4.44	0.162	0.170	0.028	4.50	0.070	309	0.014853
FY81- B[2]	34	1.185	4.22	0.120	0.095	0.031	4.70	0.053	276	-0.007897
FY81- K[2]	17	1.188	4.37	0.141	0.085	0.032	4.77	0.055	283	-0.003655
FY81- L[2]	18	1.189	4.23	0.134	0.114	0.030	4.80	0.053	281	-0.009904
FY76-78- K	10	1.167	3.88	0.114	0.120	0.030	4.23	0.055	253	0.002155
FY76-78- USGS	43	1.189	4.51	0.148	0.159	0.031	4.86	0.056	293	-0.002053
1925	18	ND	ND	0.126	0.131	ND	ND	ND	ND	ND

TDS Total Dissolved Solids, g/L
ND Not determined
[1]Calculated using method of Sturm and others, 1980, p. 175; acceptable limits are ± 0.0055 moles.
[2]Samples were collected in May.

of cation content in both sample groups, with magnesium and potassium averaging 3 and 5 percent, respectively. Although some yearly variability is evident between individual cation and anion concentrations, their respective percents of total cation and anion content remained relatively constant. Average potassium and magnesium concentrations from 18 samples of shallow-aquifer brine collected by USGS in 1925 (Nolan, 1927, Plate 3 - see appendix A1) were included for comparison with the more recent USGS and BLM samples. The 1925 potassium and magnesium concentrations are in reasonable agreement with the concentration range of the more recent samples. Although (TDS) reached a peak of 309 g/L in FY92, the TDS range from 1976 to 1981 was 253 to 293 g/L, which was similar to the 1993-2000 range of 244 to 297 g/L.

The use of mole ratios to help classify geologic processes and their products is a common geochemical practice. Ratios have been used to help distinguish between two different water sources (White, 1955, p. 148) and to help understand crystallization pathways in brines (Krauskopf, 1967, p. 341-343). More recently, Kohler (this volume) used K/Mg and Ca/SO_4 molar ratios to compare differences between brines from the Great Salt Lake and the Newfoundland Basin. Mole ratios are used in this paper to:

• Identify any subtle variability or trends in shallow-aquifer brine chemistry.
• Determine if shallow-aquifer brine chemistry is affected by laydown brine.

Mole ratios of K/Mg, Cl/Na, and SO_4/Ca were calculated from average molar concentrations of the BLM and USGS shallow-aquifer samples listed in table 9. The BLM and USGS shallow-aquifer samples comprise 13 suites of sam-

ples, and their respective mole ratios are compared in table 10.

Historically, the Cl/Na ratio was the most stable over time, ranging from 1.052 to 1.135. All reported values were within 4.2 percent of the mean (1.089) for 12 sample suites. The 13th sample suite (composed of 18 samples collected in 1925) was analyzed for potassium and magnesium only, so it is not included in the discussion of Cl/Na and SO_4/Ca ratios. This stability, and the ratio near 1:1, are consistent with the probability that the sodium and chloride concentrations of the shallow-aquifer brine are controlled by dissolution and precipitation of halite.

The SO_4/Ca was more variable, with values ranging from 1.532 to 2.475. The variation from the mean value of 2.002 was as much as 24 percent. The K/Mg ratio was the most variable of the three ratios, with values ranging from 0.604 to 1.234. Values varied from the mean (0.952) by as much as 37 percent.

Why K/Mg ratios for 5 of 13 suites (three sample suites collected by USGS in 1981 and two sample suites collected by BLM in 1994 and 1995) were 37 percent less than a ratio of about 1.0 is unknown. The 1981 USGS samples (which had the lowest ratios) were the only monitoring-well samples collected during the spring (May). This time of collection may have had some effect on the K/Mg ratio, although dilution alone should not have changed the ratio.

The BLM's FY94 and FY95 samples (with ratios of 0.721 and 0.805) were collected in the fall (September) when their concentrations were at a maximum due to effects of summer evaporation. Mason and Kipp (1998, p. 26, 55) reported wetter than normal conditions on BSF during the winter and summer months of 1993, which resulted in extensive flooding of the salt crust. Lower K/Mg ratios for the FY94 and FY95 samples could possibly be a delayed effect

Table 10. Comparison of average mole ratios from 13 suites of shallow-aquifer brine samples (from monitoring wells - MW, and auger holes - AH).

SAMPLE SUITES	n	Average Mole Ratio		
		K/Mg	Cl/Na	SO_4/Ca
BLM-MW: 1994-2000				
FY2K	10	1.080	1.093	1.532
FY97	20	1.234	1.072	2.085
FY96	16	1.108	1.109	2.403
FY95	13	0.805	1.054	2.000
FY94	19	0.721	1.118	2.468
USGS-MW (Mason et al., 1995): 1992-1993				
FY93	20	0.900	1.013	2.119
FY92	26	1.054	1.013	2.486
USGS (CD[1]): 1981				
B (AH)	34	0.791	1.114	1.699
K (MW)	17	0.604	1.093	1.732
L (AH)	18	0.855	1.135	1.752
USGS-MW (Lines, 1978): 1976-1978				
K	10	1.054	1.089	1.812
USGS	43	1.078	1.079	1.817
USGS-AH (Nolan, 1927): 1925	18	1.040	ND	ND
ND Not determined				
[1]Conservation Division				

of these conditions, if: 1) potassium and magnesium were leached from lacustrine clays or marine sedimentary rocks adjacent to BSF, and 2) slow, lateral subsurface inflow transported the additional potassium and magnesium towards BSF (Turk, 1969, p. 156-158). However, the average K/Mg ratio for nine of the monitoring-well samples collected by USGS during late June 1993 was 1.02.

The FY2K monitoring-well samples had the potential to be affected by two years of laydown brine delivery. However, the average FY2K K/Mg mole ratio (1.080) was generally in good agreement with sample suites that pre-dated the start of the Laydown Project (the exceptions were the three 1981 sample suites that were collected in the spring, and the FY94 and FY95 sample suites). In contrast, the FY2K SO_4/Ca mole ratio (1.532) was significantly lower and differed from the 12 sample-suite mean by 23 percent (there were no sulfate and calcium data for the 1925 sample suite). The lower ratio was due to a lower average sulfate concentration and a higher average calcium concentration. The cause of this difference is unknown. Additional, yearly shallow-aquifer brine samples will be required to see if a trend exists or if this ratio is part of the natural variability.

Comparison of Laydown Brine with Shallow-Aquifer Brine

Although the FY98 laydown brine contained about 15 to 64 percent less salt (as indicated by solution density) than the FY2K BSF shallow-aquifer brine, the FY99 and FY2K laydown-brine values were close in density to those of the shallow-aquifer brine (table 11). Overall composition of the lay-

down brine was generally similar to that of the BSF shallow-aquifer brine in that sodium and chloride were the dominant ions in both waters. On average, sodium made up 98 percent of the cation content in the laydown brine and 90 percent of that in the shallow-aquifer brine. Chloride made up nearly 98 percent of the anions in both waters. Concentrations of sodium and chloride in the FY2K laydown brine were 16 and 8 percent higher than those in the FY2K shallow-aquifer brine. The slightly elevated values are not unexpected because NaCl is the main salt present in PP no. 4.

Compared to sodium and chloride, magnesium, potassium, calcium, and sulfate were present in relatively low concentrations in both shallow-aquifer and laydown brines. Potassium and magnesium made up 5 and 4 percent of the average cation content for the FY94-2K shallow-aquifer brines. However, magnesium and potassium concentrations in the laydown brines were an order of magnitude less than those in the shallow-aquifer brine. Traces of potassium and magnesium in the laydown brine may have been contributed from microscopic volumes of shallow-aquifer brine entrapped as fluid inclusions in the precipitated halite in PP no. 4, and possibly entrained in the pore spaces between halite crystals. Recent microscopic examination of similar halite salt-crust samples from an adjacent Great Salt Lake Desert basin revealed presence of fluid inclusions in the halite (B. F. Jones, Research Geochemist, USGS, personal communication, September 5, 2000). Calcium concentrations in the two waters were similar, while sulfate concentrations in the laydown brine were about half those in the shallow-aquifer brine (table 11).

The mineral species that precipitate from a given solution upon evaporation, and the mass of minerals precipitated,

Table 11. Five years of shallow-aquifer brine analyses from selected BSF monitoring wells (MW) compared with 3 years of laydown-brine analyses; samples collected by BLM and analyzed by CMS.

SAMPLE SUITE	n	Density	Average Major Ion Concentrations, moles/L							Avg Mole Balance[1]
			Na	Mg	K	Ca	Cl	SO₄	TDS	
BSF MW Brine[2]										
FY2K	10	1.173	3.74	0.102	0.110	0.033	4.09	0.051	244	0.003183
FY97	20	1.185	3.95	0.109	0.134	0.028`	4.24	0.058	256	0.001462
FY96	16	1.182	4.11	0.140	0.155	0.021	4.56	0.051	282	0.003822
FY95	13	1.196	4.47	0.189	0.152	0.026	4.71	0.052	286	0.010115
FY94	19	1.192	4.47	0.224	0.162	0.022	5.00	0.055	297	0.002707
Laydown Brine[3]										
FY2K	30	1.164	4.33	0.012	0.014	0.033	4.43	0.031	262	0.004198
FY99	27	1.185	4.29	0.013	0.009	0.034	4.45	0.031	261	0.004801
FY98A	9	1.058	1.34	0.005	0.005	0.016	1.32	0.016	80	0.001891
FY98B	8	1.130	3.16	0.008	0.008	0.025	3.33	0.026	195	0.006570

TDS Total Dissolved Solids, g/L

[1] Calculated using method of Sturm and others (1980, p. 175); acceptable limits are ± 0.0055 moles.

[2] Samples collected in August and/or September from selected BSF monitoring wells in a 27-well suite.

[3] With exception of FY98A and B, average sampling frequency was two times per month (Nov through April); FY98A and B were collected in January and March-April 1998, respectively.

are dependent on the solution composition. The elevated concentrations of sodium and chloride in the laydown brine indicate that more halite will precipitate from a unit volume of laydown brine than from the same volume of shallow-aquifer brine. Conversely, the comparatively low concentrations of magnesium, potassium, and sulfate in the laydown brine indicate that minerals containing these components will be less likely to precipitate from the laydown brine than from the shallow-aquifer brine. These statements are generalizations based on evaporating fixed volumes of both brines in a closed system, contrasted with the open system of the BSF.

Predicted Mineral Precipitation from Transient-Pond Brine

The BSF transient pond currently receives input from the shallow-brine aquifer, meteoric precipitation, and the laydown Project. To identify which minerals could precipitate from the transient-pond brine, its chemistry was simulated using a range of compositions as input for TEQUIL modeling. The compositions used were those of the pre-laydown shallow-aquifer brine, the laydown brine, a 90 percent shallow-aquifer brine + 10 percent laydown mixture, a 50 percent shallow-aquifer brine + 50 percent laydown mixture, and the post-laydown shallow-aquifer brine. Effects of rainwater and shallow-aquifer brine on the minerals predicted to precipitate were also examined.

Simulation of Mixing Laydown Brine with the Transient-Pond Brine

The shallow-aquifer brine and the laydown brine represent the two compositional extremes possible for mixtures used to simulate effects of mixing laydown brine with the transient pond. Simulated transient pond compositions were

based solely on contributions from shallow-aquifer and laydown brines (input from rainfall was ignored). Two different mixtures of the two components were simulated for modeling purposes and their mixing ratios were selected based on assumptions described below.

The 90 percent shallow-aquifer brine + 10 percent laydown brine mixture simulates a condition in which the transient pond interacts with the shallow-brine aquifer as a well-mixed system. The brine volume in this system was then mixed with the laydown-brine volume delivered to BSF during FY98 through FY2K (4.5 billion gallons; table 2) (complete mixing of laydown brine with the 52.5 billion-gallon volume of the shallow-brine aquifer probably does not occur because the increased hydraulic head from addition of laydown volume reduces the upward gradient of the discharging shallow brine aquifer; however, to compute the mixing ratio, complete mixing was assumed). The volume of the BSF shallow-brine aquifer affected by the Laydown Project was estimated as 52.5 billion gallons (the transient-pond volume was assumed to be contained in this volume). This estimate was based on an average shallow-brine aquifer thickness of 20 feet, an average aquifer porosity of 0.45 percent (Mason and Kipp, 1998, p. 54), and an area of 28 square miles (identified as the affected area in the salt-replenishment feasibility study [Bingham, 1991, p. 1]). The shallow-brine aquifer and laydown brine volumes represent 92 percent and 8 percent of the total volume, respectively (100 x 52.5/[52.5 + 4.5] = 0.92; 100 x 4.5/[52.5 + 4.5] = 8). These values were rounded to 90 percent and 10 percent for modeling.

The 50 percent + 50 percent mixing ratio simulates a condition in which the transient-pond volume does not mix with the shallow-brine aquifer, and only the transient-pond volume is considered. Although it is known that the transient pond and shallow-brine aquifer are hydrologically connected, this simulation provides a case in which the laydown-brine component is larger than in the previous case. The vol-

ume of the pond was determined and mixed with the volume of laydown brine added in one year. Transient-pond volume was estimated to be about 500 million gallons per 1 inch of pond depth over an area of 28 square miles. Because transient-pond depth was reported to be from 3 inches to more than 12 inches deep in some areas (White, 1998, p. 37; Mason and Kipp, 1998, p. 55), a pond depth of 3 inches was chosen to calculate the pond volume. Monthly laydown volume averaged 290 million gallons during FY99 and FY2K. Using these conditions, the transient-pond volume could be as much as 1.5 billion gallons and total laydown volume for six months could be about 1.7 billion gallons, or nearly a 50-50 ratio.

Chemical analyses from FY94 and FY97 samples of the shallow-brine aquifer were selected as the end members that represent the compositional range of the shallow-brine aquifer. Pre-laydown transient pond composition was assumed to be similar to that of the shallow-brine aquifer. To simulate mixing the laydown brine with the transient pond, the two end members were combined with the FY2K laydown-brine composition to make two different brine mixtures (FY94 shallow-aquifer + FY2K laydown brine, and FY97 shallow-aquifer + FY2K laydown brine). Each of the brine mixtures was subdivided into a 90 percent + 10 percent and a 50 percent + 50 percent mixing ratio to make four different simulations. To calculate new cation and anion molar concentrations for the four simulations, the FY94 and FY97 shallow-aquifer and FY2K laydown brine analyses were run through the mixing function of AquaChem v. 3.7 software (Waterloo Hydrogeologic, Inc., 1998). Calculated molar concentrations from these four simulations, and an excess amount of halite, were used as inputs to the TEQUIL 25°C version. Ten moles of halite were input to simulate placing each brine mixture on the surface of halite-dominated salt crust.

TEQUIL Modeling

Description - TEQUIL is based on Pitzer electrolyte equations and calculates liquid-solid-gas equilibria in complex brine systems (Moller and others, 1997). The TEQUIL 25°C version for the Na-K-Ca-Mg-H-Cl-OH-SO_4-HCO_3-CO_2-H_2O system (Harvie and others, 1984) was selected for use in this study.

Parameters and Output - To simulate brine evaporation in a closed system, TEQUIL was constrained to reduce the original water mass in the brine by 10 percent in the first evaporation step, and then reduce the resulting new water mass by 10 percent in the second evaporation step, and so on. After 45 evaporation steps, more than 99 percent of the original water mass was depleted. The original water mass was 1,000 grams or 55.508 moles.

Output from the model lists the new brine composition from each evaporation step, and identifies the mineral species that precipitate at each step. Brine composition from each evaporation step is expressed as moles of water, major ions, and precipitated mineral species. TEQUIL uses the brine composition from the previous evaporation step as input to calculate the brine composition for the next evaporation step. This step-wise process continues until brine compositions have been calculated for all 45 evaporation

steps. In a separate output, the model also calculates cation and anion molar concentrations for the brine at each evaporation step. New molar concentrations of the brine, at any step in the simulated evaporation sequence, can be obtained for additional modeling simulations (see "Model Integrity", and "Impact of Rain and Shallow-Brine Aquifer on Predicted Potassium and Magnesium Salts").

TEQUIL-generated plots from the simulations in this paper are presented as mineral mass precipitated versus percent water remaining as evaporation progresses. Because halite mole values far exceed those of all other predicted mineral precipitates, halite is plotted on the primary Y axis, and the other predicted mineral precipitates are plotted on the secondary Y axis.

Model Integrity - To test the goodness or validity of the model, TEQUIL-predicted brine concentrations from simulated evaporation of FY96 and FY97 shallow-aquifer brine samples were compared with solar-pond brine concentrations from Reilly's potash operation at Wendover, Utah. FY96 and FY97 samples were selected because they pre-date the start of the Laydown Project. Halite and minor gypsum are the first precipitates in the commercial fractional-crystallization process, and are followed by sylvite and carnallite when concentrated brines from the primary-pond system are moved to the harvest and carnallite ponds (Bingham, 1980, p. 237-239). Brine concentrations, from the point where sylvite and carnallite first appeared in the solar ponds, were compared with modeled FY96 and FY97 brine concentrations.

Modeling showed that the first occurrences of precipitated sylvite and carnallite in the FY96 and FY97 brines usually appeared when about 93 and 97 percent of the original water mass was evaporated. At this stage of modeled evaporation, molar concentrations of the six major ions in the TEQUIL output were converted to chloride salts of sodium, potassium, and magnesium (appendix 7) and compared with solar-pond concentrations (table 12).

Table 12. Typical brine concentration as sylvite and carnallite begin to precipitate - comparison of solar-pond analyses (Bingham, 1980, p. 237-239) with TEQUIL output (concentration as wt percent in solution).

Salt	Bingham, 1980	TEQUIL - FY96	TEQUIL - FY97
First Sylvite:			
NaCl	12.5	11.6	11.9
KCl	7.5	8.7	8.8
$MgCl_2$	9.8	13.6	13.2
Density (g/mL)	1.245	1.274	1.275
First Carnallite:			
NaCl	4.0	3.2	2.9
KCl	5.0	4.1	3.8
$MgCl_2$	18.0	27.9	28.5
Density (g/mL)	1.257	1.286	1.284

Based on the TEQUIL output, the following was observed:

- Modeled concentrations were in reasonable agreement with solar-pond concentrations.

• Closer agreement was achieved between modeled and solar-pond sodium and potassium chloride salts, while modeled magnesium chloride values were about 50 percent more than solar-pond values.

Modeled magnesium values are believed to be greater than the solar-pond values because depletion of magnesium due to its adsorption on smectite clays was not accounted for in the modeling (B. F. Jones, Research Geochemist, USGS, personal communication, January 19, 2001). It is unclear why modeled density values are about 2 percent greater than the solar-pond values, because modeled initial-density values for both FY96 and FY97 monitoring well samples were in good agreement with their actual density values (for example, actual FY96 density versus modeled FY96 density was 1.182 and 1.184 g/mL, respectively).

Mineral Precipitation from Pre-Laydown Transient Pond

TEQUIL modeling was used to predict mineral precipitation from the transient pond. In the first modeling runs, chemical composition of the transient pond was assumed to be similar to that of the BSF shallow-brine aquifer. Pre-laydown shallow-brine aquifer composition was represented by chemical analyses from six years of monitoring-well samples (FY92 - FY97). Average molar concentrations of six major ions from six years of monitoring-well sample analyses (table 13) were modeled.

The minerals predicted to precipitate from the FY92-93 & FY96-97 brine compositions were nearly identical, while the FY94 and FY95 results were slightly different. Predicted mineral-species plots for FY92, FY94, and FY97 are shown in figures 9-11, and plots for FY93, FY95, and FY96 are in appendix A8, figures A8.1 -A8.3. The order of mineral precipitation (listed in order of predicted precipitation; see

appendix 9) for the various years was as follows:

• FY92-93 & FY96-97: anhydrite-halite-syngenite-sylvite-polyhalite-carnallite-kainite.

• FY94: anhydrite-halite-polyhalite-sylvite-carnallite-kainite-kieserite-bischofite.

• FY95: anhydrite-halite-polyhalite-sylvite-carnallite-kieserite.

The predicted potassium and magnesium mineral precipitates only occurred after 85 to 90 percent of the water was evaporated.

While the FY92-93 and FY96-97 mineral precipitates were identical, there was some slight variation in their respective sylvite and carnallite peak values; these were due to slight differences in potassium and magnesium concentrations in the FY92-93 and FY96-97 sample analyses. Unlike FY92-93 and FY96-97, the FY94-95 predicted mineral precipitates included kieserite, but were missing syngenite. These differences are in response to a marked increase in average FY94 and FY95 magnesium concentrations, compared to those in the FY92-93 and FY96-97 samples.

Based on differences observed from plots of TEQUIL-predicted mineral precipitates, analyses from the FY92-93 and FY96-97 samples, and the FY94-95 samples, represented the two compositional extremes of the transient pond during the sampling period. Predicted mineral-precipitate plots from the two compositional extremes were compared with those from four actual transient pond samples collected by USGS in 1993 (see table 17). The predicted mineral-precipitate plots from the June and July 1993 pond samples (appendix A10, figures A10.1 and A10.2), which were collected during peak evaporation, were nearly identical to plots from the FY92-93 and FY96-97 monitoring-well samples (see figures 9 - 11, and appendix A8, figures A8.1 - A8.3).

Table 13. Pre-laydown molar concentrations of the shallow-brine aquifer from four years of BLM monitoring-well samples and two years of USGS monitoring-well samples

Sample	n	Density	Na	Mg	K	Ca	Cl	SO$_4$
BLM Samples:								
FY97	20	1.185	3.95	0.109	0.134	0.028	4.24	0.058
FY96	16	1.182	4.11	0.140	0.155	0.021	4.56	0.051
FY95	13	1.196	4.47	0.189	0.152	0.026	4.71	0.052
FY94	19	1.192	4.47	0.224	0.162	0.022	5.00	0.055
USGS Samples:								
FY93[1]	9	1.186	4.38	0.160	0.163	0.029	4.65	0.063
FY92[1]	9	1.194	4.44	0.195	0.193	0.028	4.67	0.068

[1]These nine samples are from 9 of 26 BSF monitoring wells sampled by Mason and others (1995, p. 50, table 4) in 1992-93; these same nine wells were also sampled by BLM during 1994-97 (see appendix A1, tables A1.9-A1.10).

USGS FY92 Monitoring Well Average (n = 9)
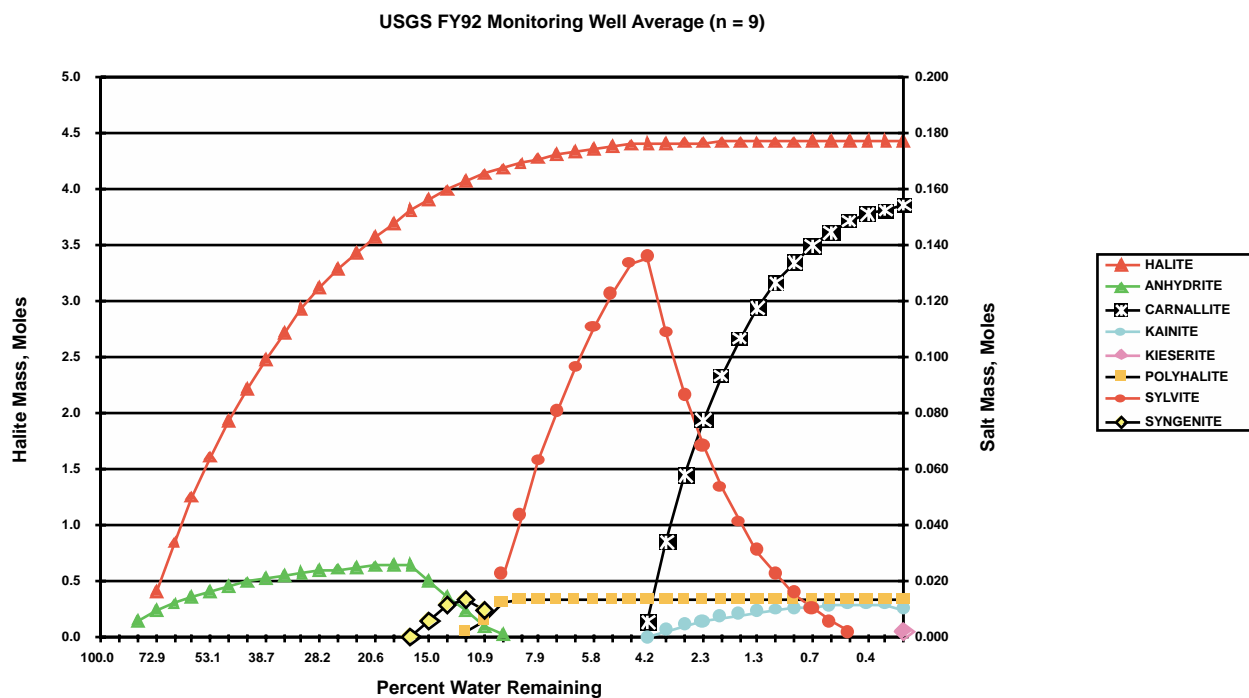
Figure 9. TEQUIL-predicted mineral precipitation plots from average analyses of USGS FY92 monitoring-well samples.

BLM FY94 Monitoring-Well Average (n = 19)
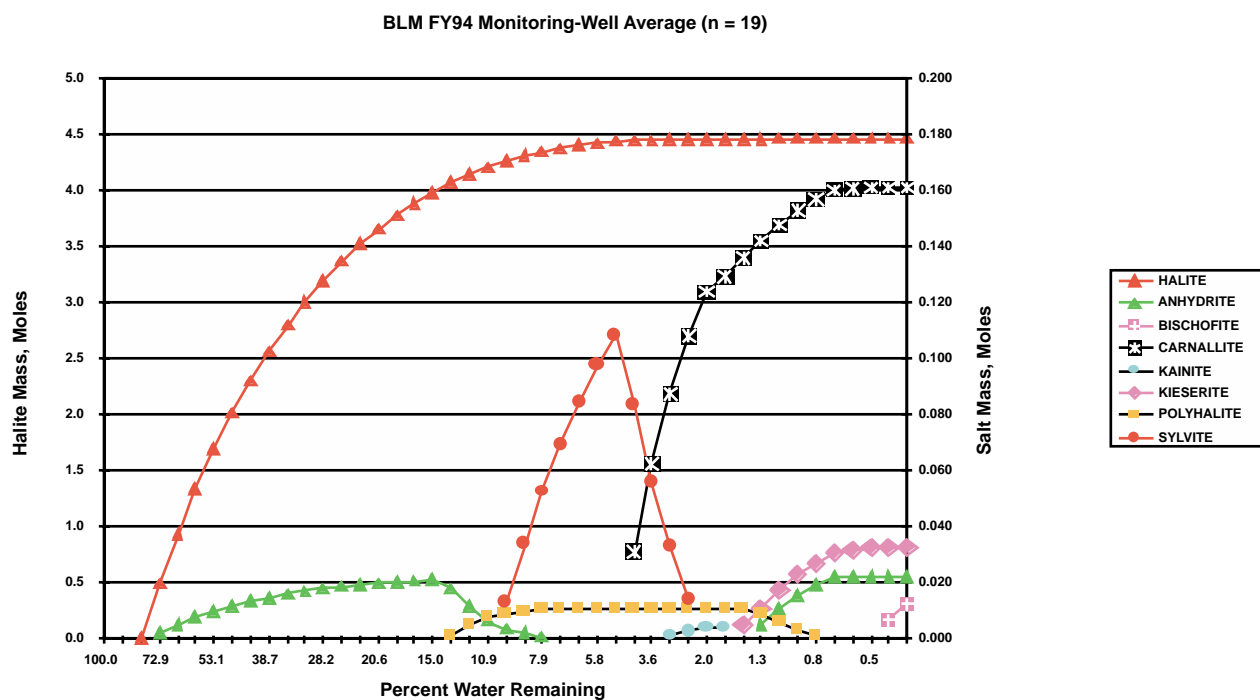
Figure 10. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY94 monitoring-well samples.

BLM FY97 Monitoring Well Average (n = 20)
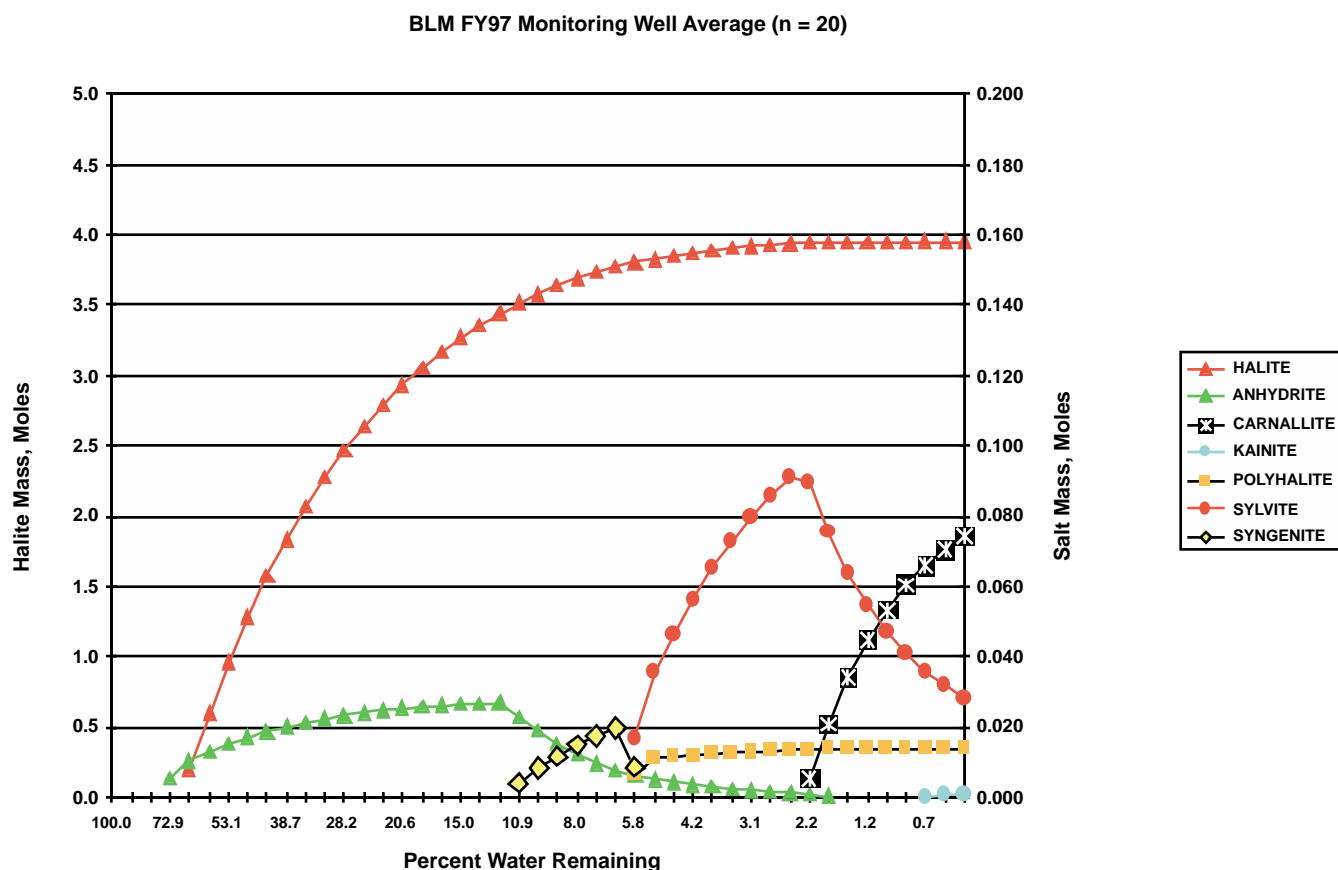
Figure 11. *TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY97 monitoring-well samples.*

To simplify the modeling of mixing the transient pond with laydown brine, FY94 and FY97 monitoring-well-sample analyses were chosen to represent the compositional range of the transient pond. FY94 was selected because its predicted mineral precipitates differed the most from the 6 years of monitoring-well samples examined. FY97 was selected because its average chemical composition was closest to shallow-brine aquifer and subsequent transient pond compositions just prior to the first delivery of laydown brine to BSF on November 1, 1997.

Mineral Precipitation from Laydown Brine

In contrast with the seven or eight minerals predicted to precipitate from the two transient-pond end members, only anhydrite and halite were predicted to precipitate from the FY99 and FY2K laydown brines. Because of their very low concentrations, all potassium and magnesium contained in these brines remained in solution after 99 percent of the water was removed (figure 12).

Mineral Precipitation from Mixtures of Transient Pond and Laydown Brines

The TEQUIL-predicted mineral precipitation from the four brine-mix simulations were essentially the same as those predicted for their end-member components (FY94 and FY97 monitoring-well brines [see figures 10 and 11]). How-

ever, as the mixing ratios were changed from 90 percent shallow-aquifer brine + 10 percent laydown brine to 50 percent + 50 percent, the first appearances of most mineral-precipitate plots were shifted to later evaporation steps, and corresponding mineral masses precipitated were reduced proportionately depending upon the mixing ratio.

Although both sets of mixing ratios approached halite saturation, they were able to dissolve additional halite (haltite saturation is equivalent to a brine density of 1.2 g/mL; average densities for FY94 and FY97 monitoring-well samples and FY2K laydown samples were 1.192, 1.185 and 1.164 g/L, respectively). TEQUIL output for both mixing ratios showed that from 1.2 to 1.9 moles (or 12 to 19 percent) of halite from the 10 moles used to simulate contact with the halite-dominated salt crust were dissolved during the first evaporation step (figures 13 - 16). The model predicted that the portion of the 10 moles dissolved in the first evaporation step would be reprecipitated by the 4th or 5th evaporation step. After the reprecipitation restored the halite 10-mole mass, halite in excess of 10 moles was contributed by Na^+ and Cl^- originally contained in the 90 percent + 10 percent and 50 percent + 50 percent mixing simulations prior to their contact with 10 moles of halite.

As was previously mentioned, the FY2K laydown brine was enriched in sodium and chloride, and depleted in potassium and magnesium. TEQUIL output at evaporation step one showed that mixing laydown brine with the two transient-pond end members generally resulted in increased con-

BLM FY2K Laydown Brine Average (n = 30)
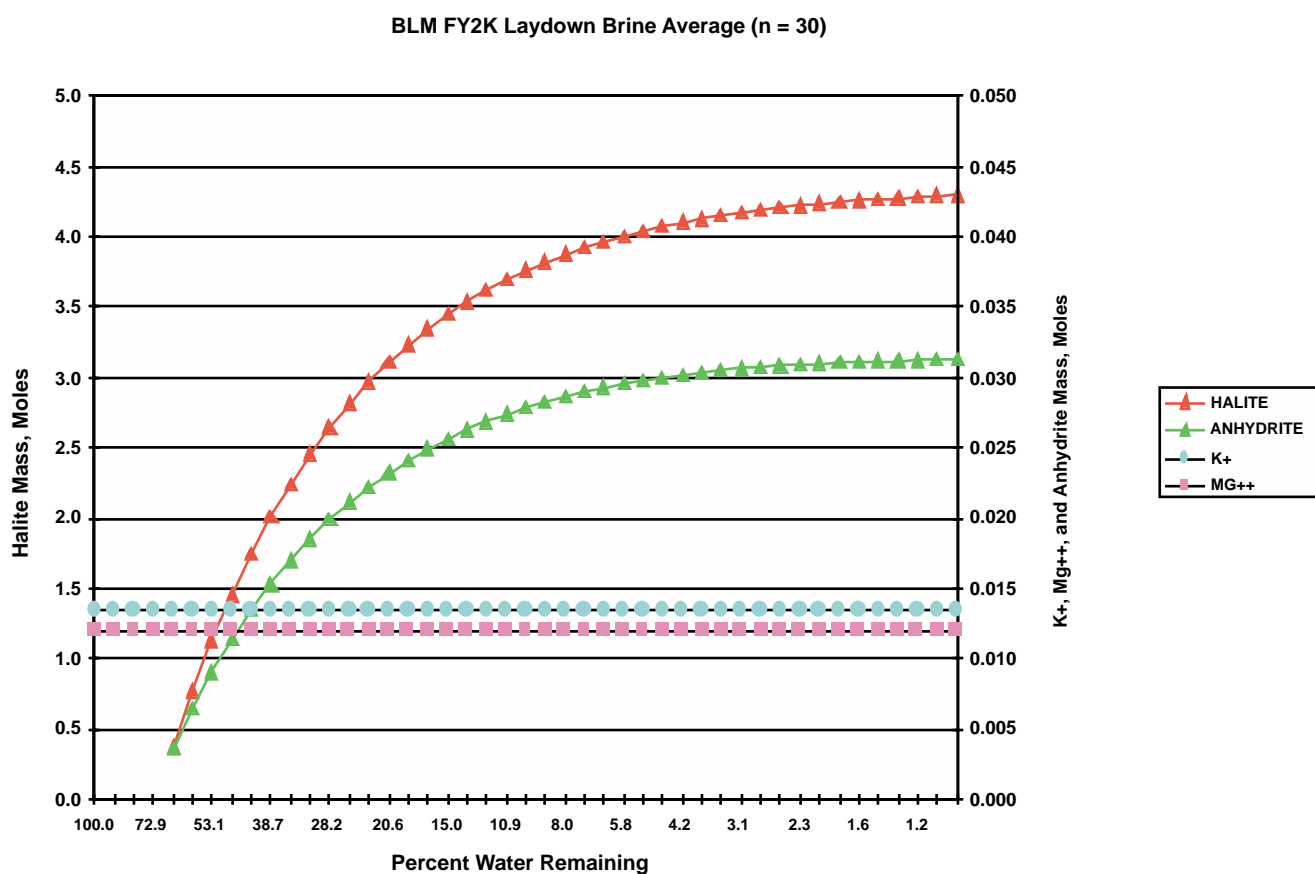
Figure 12. *TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY2K laydown-brine samples.*

FY94 Monitoring-Well + FY2K Laydown Mix (90% + 10%)
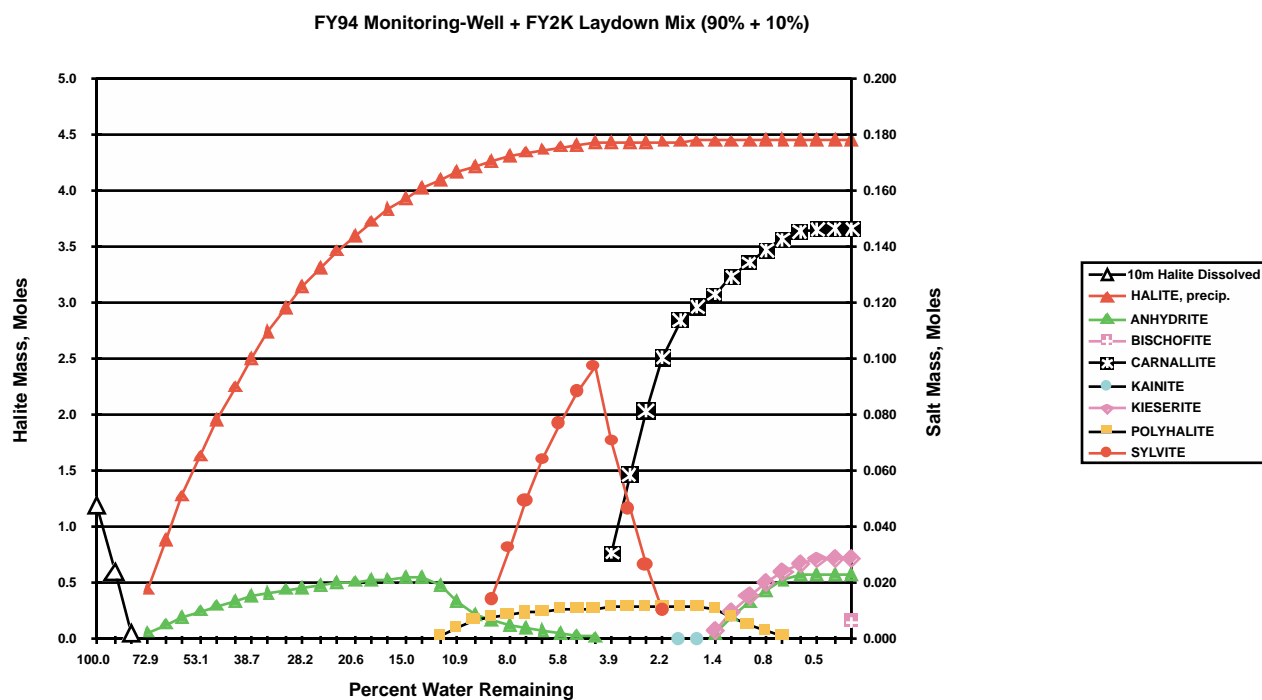
Figure 13. *TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY94 monitoring-well + FY2K laydown brines (90% + 10% mixing ratio).*

FY94 Monitoring-Well + FY2K Laydown Mix (50% + 50%)
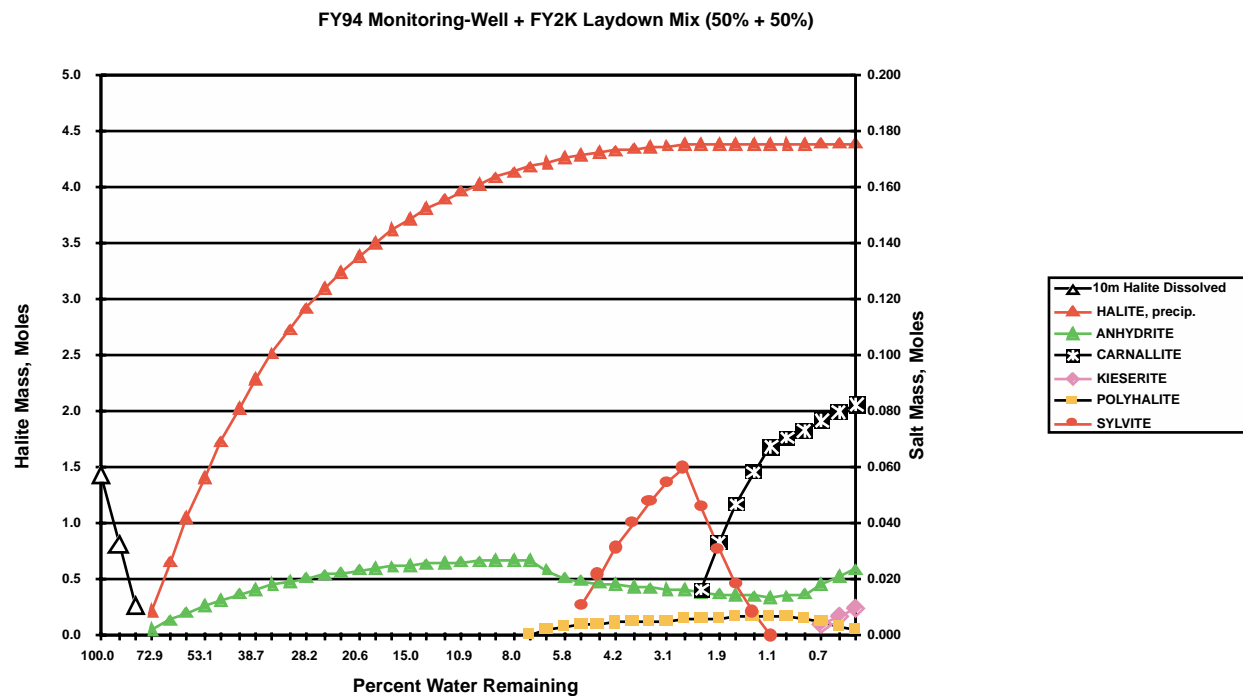
Figure 14. *TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY94 monitoring-well + FY2K laydown brines (50% + 50% mixing ratio).*

FY97 Monitoring-Well + FY2K Laydown Mix (90% + 10%)
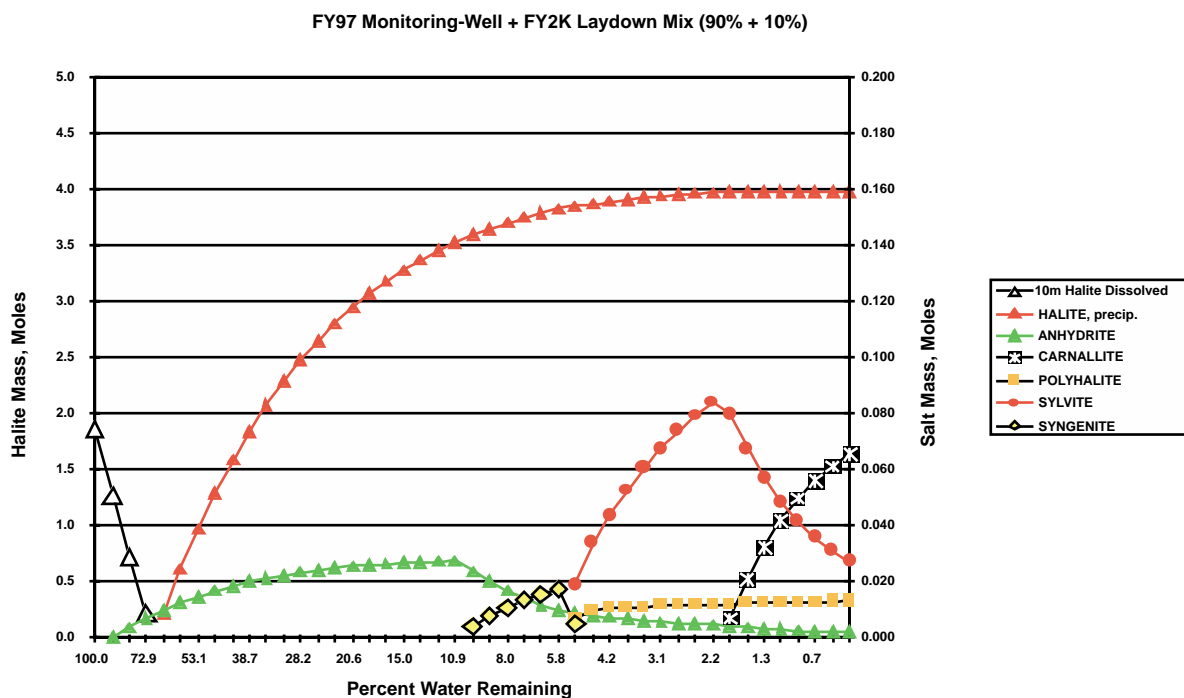
Figure 15 *TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY97 monitoring-well + FY2K laydown brines (90% + 10% mixing ratio).*

centrations of NaCl (see "Fate of laydown Brine NaCl..."), and a dilution of potassium and magnesium concentrations. Consequently, a larger reduction of original water mass was required to initiate precipitation of carnallite and sylvite. For example, first occurrence of sylvite in the FY94 monitoring-well plot (figure 10) coincided with a 90 percent reduction in original water mass; however, first occurrence of sylvite in the FY94 monitoring-well + FY2K laydown plot (50 percent + 50 percent mixing ratio) coincided with a 95 percent reduction in water mass (figure 14).

In summary, TEQUIL modeling of mineral precipitation from the four brine-mixing simulations showed the following:

• No new mineral species were introduced as a result of mixing laydown brine with transient-pond brine.

• Anhydrite and halite were the first mineral species to precipitate and were the only minerals present until the original water mass was reduced by 87 and 93 percent, respectively (figures 13 - 16).

• Potassium and magnesium mineral precipitates (sylvite and carnallite) did not appear until the original water mass was reduced by 91 to 97 percent, and 96 to 98 percent of the halite was precipitated.

• When compared with the two transient-pond end members (FY94 and FY97), the 90 percent + 10 percent and 50 percent + 50 percent mixing ratios usually had their plot positions shifted to later evaporation steps, and the maximum predicted mass of carnallite and sylvite precipitated decreased by about 10 to 70 percent depending upon the mixing ratio (compare figures 10 & 11 with figures 13 - 16).

Mineral Precipitation from Shallow-Brine Aquifer: Pre- and Post-Laydown

TEQUIL model simulations were also used to compare predicted mineral precipitation between pre- and post-laydown samples from the BSF shallow-brine aquifer. FY97 monitoring-well samples collected one month prior to the start of laydown brine delivery were selected for comparison with FY2K monitoring-well samples. FY2K samples were collected 1 month prior to the start of the third-year of laydown brine delivery to BSF. Predicted mineral-precipitate plots for FY97 and FY2K monitoring-well samples were nearly identical (figures 11 and 17):

• Predicted mineral precipitates were the same for both monitoring-well samples; halite and gypsum were the first minerals to precipitate and were the only minerals present until 90 percent of the original water mass was evaporated.

• Relative positions of the sylvite and carnallite plots were the same for both samples; sylvite and carnallite first occurrences appeared when evaporation reduced the original water mass by 94 and 98 percent, respectively, and 96 percent of the halite precipitated.

• Maximum predicted masses for carnallite were the same for FY97 and FY2K (0.075 moles).

• Maximum predicted masses for sylvite were nearly the same for FY97 and FY2K (0.091 and 0.079 moles, respectively).

FY97 Monitoring-Well + FY2K Laydown Mix (50% + 50%)
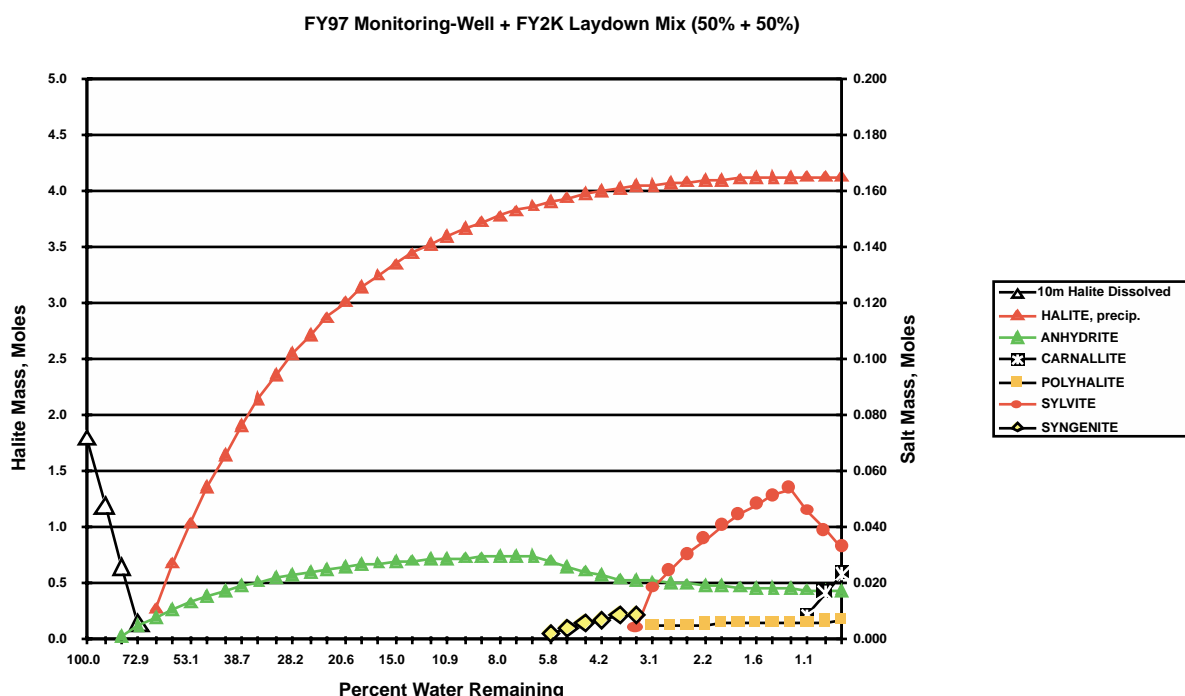
Figure 16. TEQUIL-predicted mineral precipitation plots from a mixing simulation of FY97 monitoring-well + FY2K laydown brines (50% + 50% mixing ratio).

BLM FY2K Monitoring Well Average (n = 10)
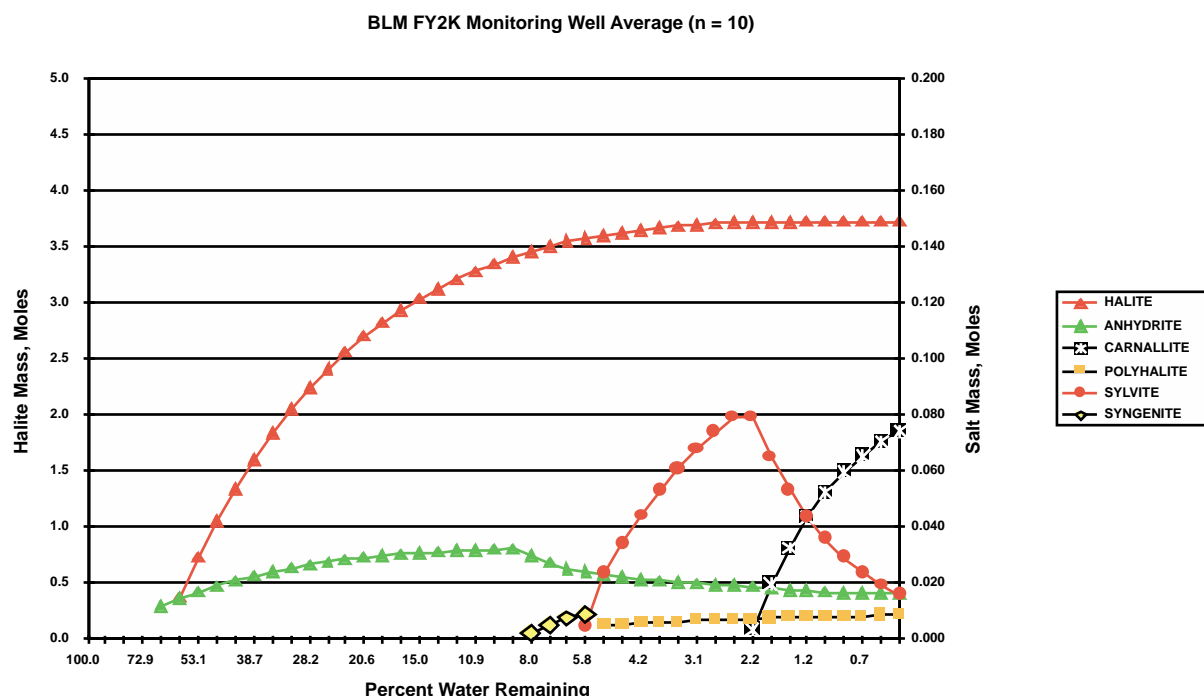
Figure 17. TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY2K monitoring-well samples.

Impact of Rain and Shallow-Brine Aquifer on Predicted Potassium and Magnesium Salts

Potassium and magnesium mineral species predicted in the previous closed-system simulations resulted because TEQUIL was constrained to evaporate a fixed volume of brine to dryness without its being replenished by rainfall or the shallow-brine aquifer. However, in a recent mineralogic examination of salt-crust samples from a natural open system, neither potassium or magnesium minerals were observed with the halite and gypsum.

To understand why potassium and magnesium minerals were absent from these salt-crust samples, and to determine the efficacy of potassium and magnesium mineral formation in an open system, two additional mixing simulations were modeled with TEQUIL:

• 50 percent transient pond + 50 percent rainwater, and

• 50 percent transient pond + 50 percent shallow-aquifer brine.

These simulations were considered to be a more realistic representation of open-system effects from addition of rainwater and shallow-aquifer brine to an evaporating transient pond. Prior to being mixed either with rainwater, or with shallow-aquifer brine, it was assumed that the transient pond's water volume was reduced by 95 percent through evaporation. This extreme volume reduction was required to produce potassium and magnesium mineral precipitates whose fate could then be determined by mixing with rainwater or shallow-aquifer brine. Because of the variety of potassium and magnesium salts predicted to precipitate by TEQUIL, in the closed-system modeling of FY94 monitoring-well brine, FY94 chemical analyses were used to approx-

imate the transient pond and shallow-aquifer brine compositions in the simulations.

Evaporated transient-pond brine composition was simulated by using the TEQUIL-predicted concentrations of the FY94 monitoring-well brine at the point where its water volume was reduced by 95 percent (table 14). At this point, sylvite and polyhalite precipitation approached peak values and carnallite precipitation first occurred (see figure 10).

Shallow-aquifer brine composition was represented by average chemical analyses of the FY94 monitoring-well brine (see table 13). Rainwater composition was taken from Hem (1989) (table 15). The mixing function of AquaChem v. 3.7 (Waterloo Hydrogeologic, Inc., 1998) was used to calculate new cation and anion molar concentrations from mixing evaporated transient pond with rainwater and with shallow-aquifer brine. These new cation and anion concentrations were the aqueous-phase input to TEQUIL for modeling both transient-pond mixing simulations (table 16). Because the precipitated minerals listed in table 14 were in equilibrium with the evaporated transient-pond composition, their mole values were also included as solid-phase input to the modeling.

TEQUIL-generated plots from the two simulations showed that potassium and magnesium minerals from the evaporated transient pond were re-dissolved when mixed with rainwater or shallow-aquifer brine. Halite and anhydrite were the only salts to precipitate during the first four evaporation steps of the TEQUIL output (figures 18 and 19).

To illustrate the difference between open-system conditions and those required for potassium and magnesium mineral precipitation, brine analyses from four transient-pond samples collected by USGS in 1993 were compared with TEQUIL-predicted brine concentrations from the two transient-pond mixing simulations (table 17). The simulation

50-50 Mix of Transient Pond (plus its precipitated salts) with Rainwater
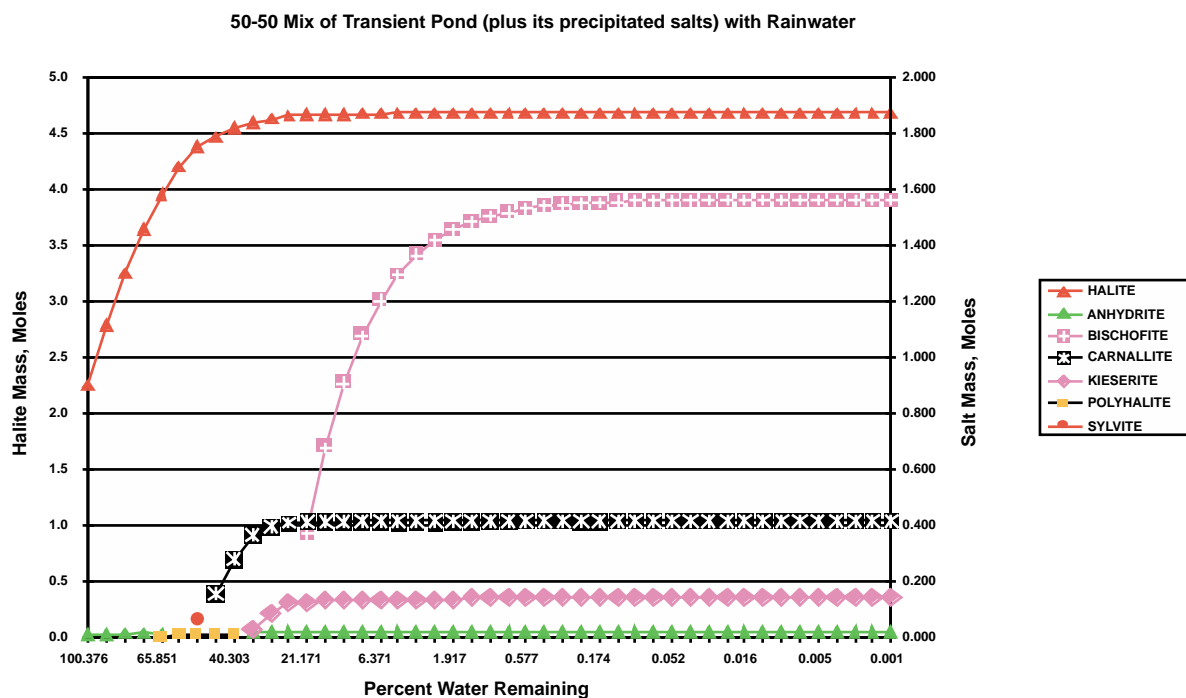
Figure 18. *TEQUIL-predicted mineral precipitation plots from a mixing simulation of evaporated FY94 monitoring-well brine + rainwater (50% + 50% mixing ratio. Note: original water mass is greater than 100% because model accounted for water of hydration contained in salts that were used as solid-phase input to the model (see table 14).*

50-50 Mix of Transient Pond (plus its precipitated salts) with Shallow-Aquifer Brine
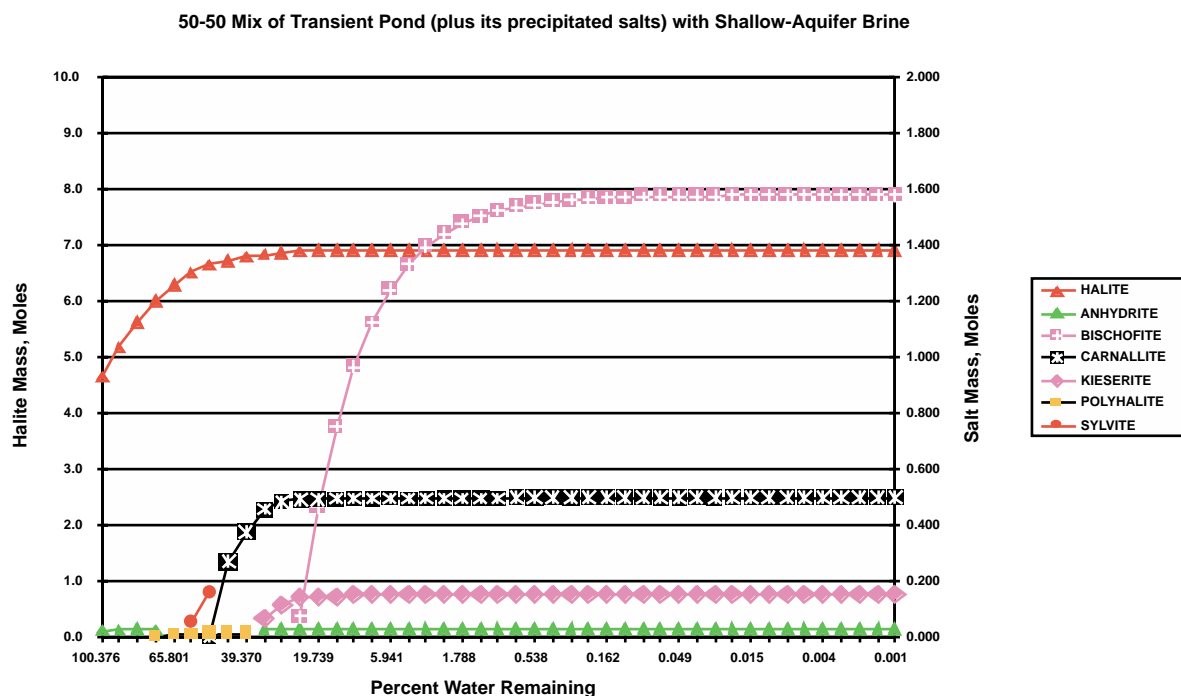
Figure 19. *TEQUIL-predicted mineral precipitation plots from a mixing simulation of evaporated FY94 monitoring-well brine + shallow-aquifer brine (50% +50% mixing ratio). Note: original water mass is greater than 100% because model accounted for water of hydration contained in salts that were used as solid-phase input to the model (see table 14).*

Table 14. Simulated transient pond composition from TEQUIL-predicted concentrations of FY94 monitoring-well brines after water volume was reduced by 95 percent.

Aqueous-phase Species, moles/L		Solid-phase Species, moles	
Na^+	0.483	Carnallite	0.031
K^+	0.566	Halite	4.452
Ca^{2+}	0.001	Polyhalite	0.011
Mg^{2+}	4.174	Sylvite	0.084
Cl^-	8.916		
$SO4^{2-}$	0.242		

Table 15. Rainwater composition (from Hem, 1989, p. 36, table 6, item 2).

Species	mg/L	moles/L
Na^+	0.56	0.000024
K^+	0.11	0.000003
Ca^{2+}	0.65	0.000016
Mg^{2+}	0.14	0.000006
Cl^-	0.57	0.000016
SO_4^{2-}	2.18	0.000023
HCO_3^-	0.42	0.000007

[1]Bicarbonate was added to achieve charge balance required by TEQUIL.

Table 16. Molar concentrations used as input for TEQUIL simulations of evaporated transient pond mixed with rainwater and with shallow-aquifer brine.

Sample	Na	Mg	K	Ca	Cl	SO$_4$
Transient Pond[1] + rainwater	0.241	2.087	0.283	0.001	4.458	0.121
Transient Pond[1] + Shallow-aquifer brine	2.487	2.199	0.364	0.012	6.958	0.148

[1]Original volume reduced by 95%

Table 17. Molar concentrations from four USGS samples of the 1993 transient pond and from two TEQUIL simulations of evaporated transient pond mixed with rainwater and with shallow-aquifer brine.

Sample	Na	Mg	K	Ca	Cl	SO$_4$
1993 Transient Pond Near BLM-93:[1]						
January 21	4.349	0.005	0.010	0.027	4.513	0.029
May 13	4.785	0.023	0.041	0.037	4.231	0.046
June 16	5.219	0.053	0.072	0.042	4.231	0.044
July 7	4.872	0.132	0.207	0.035	5.416	0.054
TEQUIL Simulations:						
Transient Pond[2] + rainwater	0.308	2.118	0.334	0.001	4.637	0.121
Transient Pond[2] + Shallow-aquifer brine	0.412	2.225	0.412	0.001	5.022	0.127

[1]From Mason and others (1995, p. 50, table 4).
[2]Original volume reduced by 95 percent

concentrations were selected from the point where sylvite first occurred in the modeled output (or the point where nearly 50 percent of the original water mass was evaporated).

Two marked differences were observed:

• Sodium concentrations from the four 1993 transient-pond samples were more than 10 times the sodium concentrations predicted for the two transient-pond mixing simulations.

• Potassium and magnesium concentrations from July 1993 transient-pond samples were about one-half and one-seventeenth of corresponding mixing-simulation concentrations.

Despite the occurrence of peak evaporation on the salt crust during June 1993 (Mason and Kipp, 1998, p. 34), the sodium concentration of the June pond sample was still 10 times that of the two simulations. Before potassium and magnesium minerals could precipitate from the 1993 transient pond, the pond would have to be evaporated to the point where 99.5 percent of its sodium was precipitated as halite, and it remained in the solid phase. This is unlikely in an open system where the transient pond receives seasonal rain-water and is connected with the shallow-brine aquifer. The 1993 transient-pond brine would have to subjected to closed-system conditions similar to the commercial solar-pond process (Bingham, 1980, p. 237-239) in order for its composition to approach that of the two transient-pond mixing simulations shown in table 17.

Fate of Laydown-Brine NaCl When Mixed With the Shallow-Brine Aquifer

In the first three years of the Laydown Project, 4.6 million tons of NaCl were delivered to BSF. However, the amount of laydown NaCl precipitated as salt crust versus the amount of NaCl that remained in solution in the shallow-brine aquifer was unknown. TEQUIL outputs from previously described simulations were examined to see if the fate of laydown NaCl could be quantitatively described.

TEQUIL output from 90 percent shallow brine aquifer brine + 10 percent laydown brine and 50 percent + 50 percent mixing ratios, that were contacted with an excess of halite (10 moles), showed that the simulated solutions could dissolve additional NaCl. Based on this output, TEQUIL was used to determine how much of the 4.6 million tons could be assimilated by the shallow-brine aquifer within the 28 square mile area of BSF affected by the Laydown Project. Model output from each of the following brines and brine-mixture simulations was examined: 1) pre-laydown transient pond end members (FY94 and FY97 MW samples), 2) laydown brine (FY2K LD), and 3) 90 percent shallow-brine aquifer brine + 10 percent laydown brine and 50 percent + 50 percent mixing ratios of the FY94 MW + FY2K LD and FY97 MW + FY2K LD simulations. TEQUIL-calculated moles of sodium from the first evaporation step of these simulations were converted to pounds and tons of NaCl dissolved per gallon (table 18).

Based on the TEQUIL output at the first evaporation step (table 18), the transient-pond end members (FY94 MW and FY97 MW) contained 2.179 lbs/gal (1.089 X 10^{-3} tons/gal) and 1.926 lbs/gal (0.963 X 10^{-3} tons/gal) of dissolved NaCl, respectively. When FY94 MW and FY97 MW were compared to their corresponding 50-50 mixtures, the dissolved NaCl weight increased to 2.842 lbs/gal (1.421 X 10^{-3} tons/gal) and 2.896 lbs/gal (1.448 X 10^{-3} tons/gal), respectively. When the weight of dissolved NaCl in the 50-50 mix is subtracted from the weight of dissolved NaCl in the transient-pond end member, this results in an increased capacity of 0.663 lbs/gal (0.332 X 10^{-3} tons/gal) and 0.97 lbs/gal (0.485 X 10^{-3} tons/gal) for FY94 MW and FY97 MW.

When the increased capacity is multiplied by the 52.5 billion-gallon volume of the shallow-brine aquifer affected by the Laydown Project, the FY94 MW and FY97 MW end members could accommodate 17 and 25 million tons of additional NaCl, respectively. This is about four to five times the 4.6 million tons delivered to BSF by the Laydown Project. This suggests that the 4.6 million tons could initially be assimilated into the shallow-brine aquifer as NaCl in solution.

The capability of the shallow-brine aquifer to accept additional NaCl is significant, because it is the shallow-brine aquifer that regulates the distribution of NaCl mass to the BSF salt crust. If the laydown NaCl mass is assimilated by the shallow-brine aquifer, then: 1) one would anticipate an increase of NaCl concentration in the affected area of the shallow-brine aquifer, and 2) it would not be unreasonable to expect that more halite mass would be added to the existing salt crust as a result of this increased NaCl concentration.

Based on salt-crust monitoring using Landsat 5 imagery, thickness measurements, and geochemical modeling, new

Table 18. TEQUIL-calculated moles of Na at the first evaporation step converted to pounds and tons of NaCl dissolved per gallon of brine.

Sample	Na, moles	NaCl, lbs/gal	NaCl, tons/gal ($*10^{-3}$)
FY94 MW (n=19)	4.473	2.179	1.089
FY97 MW (n=20)	3.954	1.926	0.963
FY2K LD (n=30)	4.328	2.108	1.054
90% + 10% 94 + 2K[1]	5.666	2.760	1.380
50% + 50% 94 + 2K[1]	5.835	2.842	1.421
90% + 10% 97 + 2K[1]	5.866	2.857	1.428
50% + 50% 97 + 2K[1]	5.947	2.896	1.448

[1]Includes 10 moles of halite to simulate contact with salt crust.

halite deposition from 3 years of brine delivery by the Lay-down Project is probably distributed into:

- Increased salt-crust area (5-square mile increase since 1997),

- Increased dissolved solids in the shallow-brine aquifer (with NaCl assimilation capacity of 17 to 25 million tons), and

- Thickened halite strata (dense-cemented halite, cemented-coarse-porous halite, and uncemented-coarse halite strata) that comprise the 26-square mile area of salt crust existing as of 1997.

CONCLUSIONS

Three years of Salt-Laydown Project operation have demonstrated that annual salt-tonnage loss from BSF can be replenished by the laydown facility. During this period, a sodium chloride salt mass of 4.6 million tons was delivered to BSF. The average annual addition of 1.5 million tons exceeded the estimated annual salt loss of 0.85 million tons.

The salt addition appears to be distributed between new salt-crust area, various salt-crust strata, and the shallow-brine aquifer.

Monitoring during the project produced the following conclusions regarding changes in salt crust thickness, areal extent and mass:

- At least five different strata comprise the salt-crust; thickness measurements of the dense-cemented halite stratum and the cemented-coarse-porous halite stratum showed substantial thickness changes from year to year, while little change in total salt-crust thickness was observed at nine locations during a 10-year period.

- Based on salt-thickness comparisons from 1994 to 2000, the dense-cemented halite stratum thickness increased at one location and decreased at three other locations; however, cemented-coarse-porous halite stratum thicknesses increased when the dense-cemented halite stratum thicknesses decreased at the same locations.

- An unusually wet (or dry) year could measurably decrease (or increase) the thickness of the dense-cemented halite stratum from year to year.

- Although the yearly laydown tonnage would maintain or increase the current mass of NaCl in the salt-crust deposit and shallow-brine aquifer, annual variation in dense-cemented halite stratum could easily mask the annual 0.4-inch increase in salt-crust thickness predicted by the laydown feasibility study.

- Depending upon the amount of halite dissolved from the dense-cemented halite stratum, an apparent thinning of the dense-cemented halite stratum could occur during unseasonably wet years in spite of increased salt tonnage added to BSF by the Laydown Project.

- An estimated 17 percent (5-square mile) increase in salt-crust areal extent was observed between September 1997 and October 1999 (the first laydown brine was delivered to BSF November 1, 1997).

- Using the new 5-square mile area of salt crust, assumed thickness of 0.25 to 1 inch, and bulk salt densities of 79.4 and 109.8 pounds per cubic foot, an estimated 0.1 to 0.6 millions tons of salt was added to the salt crust as new area by the Laydown Project; the remainder was apparently distributed to the main body of the salt crust (26 square miles in 1997), and to the shallow-brine aquifer.

Geochemical modeling of brine compositions, determined during the project, produced the following conclusions regarding salt addition to the shallow-brine aquifer:

- The TEQUIL model accurately predicted chemistries, based on agreement between modeled output and solar pond brine compositions from a commercial potash operation.

- The model also showed that the shallow brine aquifer has the capacity to accept 17 to 25 million tons of NaCl; this tonnage is four to five times the 4.6 million tons of laydown salt delivered to BSF during the first three years of the Laydown Project.

- The ability of the shallow-brine aquifer to assimilate additional salt may help account for the laydown-delivered salt tonnage that was in excess of the amount estimated in the 5 square miles of new salt crust.

- The laydown NaCl mass assimilated into the shallow-brine aquifer is eventually redistributed in the salt crust as part of new surface and additional subsurface halite crystal growth.

- The addition of laydown brine to the shallow-brine aquifer does not change the salt-crust mineral assemblages; anhydrite and halite were the only minerals predicted to precipitate from two different mixing ratios of laydown brine and shallow-aquifer brine in an open system such as BSF.

- Potassium and magnesium salts do not precipitate in an open system such as BSF; the addition of rainwater or the shallow-aquifer brine dissolves them immediately. All TEQUIL simulations showed that more than 90 percent of the water would have to be evaporated, and 96 to 98 percent of the NaCl would have to be precipitated before potassium and magnesium minerals precipitated from the brine; this condition could only be achieved if a mixture of laydown brine and shallow-aquifer brine were isolated from the shallow-brine aquifer and subjected to conditions similar to a commercial solar-pond process.

CONSIDERATIONS FOR CONTINUED ASSESSMENT

To continue the assessment of the Laydown Project's effectiveness, thickness measurements from a larger population of drill holes are needed, and an additional 42 to 70 auger holes per year are recommended:

The number of holes is based on drilling three to five holes on each of Brooks' (1991, figure 4) 14 drill-hole transects across the International Track.

The same number of holes would be drilled each year close to the same points on each transect, and total salt-crust thickness measurements would be recorded.

Additionally, each stratum thickness should be measured and compared with total salt-crust thickness at each specified sample site; using the thickness changes in the dense-ce-

mented halite stratum alone may be misleading.

Purchase and use of satellite imagery should continue so that changes in salt-crust areal extent can be monitored; salt-crust thickness measurements should be made adjacent to monitoring wells that are located near the east margin of the salt crust so that new salt-crust area tonnages can be calculated.

ACKNOWLEDGMENTS

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Note: The use of brand names in this paper does not imply endorsement of any product by Reilly, BLM, or Department of Natural Resources.

APPENDIX A1

PRE-1994 BSF MONITORING-WELL SAMPLE ANALYSES BY USGS

Table A1.1. Summary of 18 auger-hole brine samples collected on and adjacent to BSF (Nolan 1927, Plate 3); concentrations expressed in g/L and moles/L.

Sample	g/L		moles/L	
	Mg	**K**	**Mg**	**K**
1	0.4	1	0.016	0.026
2	1.3	2.8	0.053	0.072
3	3.4	4.6	0.140	0.118
5	6.4	10.2	0.263	0.261
8	7.3	12.5	0.300	0.320
9	4.8	8.7	0.197	0.223
10	7.2	12.2	0.296	0.312
11	5.9	9.2	0.243	0.235
12	3.9	7.4	0.160`	0.189
13	2.3	4.2	0.095	0.107
14	2.2	4	0.091	0.102
15	1.6	2.9	0.066	0.074
16	2.8	3.7	0.115	0.095
17	2.1	3.2	0.086	0.082
23	0.3	0.7	0.012	0.018
255	0.5	1.1	0.021	0.028
260	0.5	0.9	0.021	0.023
265	2.2	3.2	0.091	0.082
Mean	3.1	5.1	0.126	0.131
Minimum	0.3	0.7	0.012	0.018
Maximum	7.3	12.5	0.300	0.320

Table A1.2. Summary of 43 "USGS" BSF monitoring-well brine samples (Lines, 1978; Lines, 1979); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
USGS-29/30	10/02/78	1.202	120.0	3.20	7.10	1.20	180.0	5.60	317.0
USGS-29/30	10/12/77	1.198	110.0	4.10	6.20	1.20	180.0	5.50	307.0
USGS-29/30	10/02/78	1.200	120.0	1.20	2.70	1.30	190.0	4.70	320.0
USGS-29/30	10/26/77	1.200	120.0	1.40	3.10	1.40	180.0	5.20	311.0
USGS-74	09/23/76	1.196	100.0	5.70	9.20	1.10	180.0	5.30	301.0
USGS-31/32	09/27/76	1.189	110.0	0.96	2.40	1.50	180.0	4.10	299.0
USGS-31/32	09/27/76	1.202	120.0	1.40	2.90	1.40	190.0	4.00	320.0
USGS-23	09/27/76	1.204	110.0	3.00	7.00	1.30	190.0	4.30	316.0
USGS-23	09/27/76	1.198	100.0	4.60	8.40	1.20	180.0	5.00	299.0
USGS-8	09/24/76	1.202	120.0	1.70	4.00	1.80	190.0	3.80	321.0
USGS-8	09/24/76	1.198	110.0	2.80	4.90	1.30	190.0	4.40	313.0
USGS-9	09/24/76	1.197	100.0	5.50	9.60	1.00	180.0	6.20	302.0
USGS-9	10/02/78	1.200	100.0	5.70	11.00	0.92	180.0	7.10	305.0
USGS-9	10/11/77	1.198	110.0	5.80	9.20	1.00	180.0	6.60	313.0
USGS-10	10/02/78	1.205	110.0	2.90	6.10	1.10	180.0	5.10	305.0
USGS-10	09/24/76	1.201	110.0	5.50	9.30	0.96	200.0	5.90	332.0
USGS-10	10/26/77	1.203	110.0	3.30	5.50	1.20	170.0	4.90	295.0
USGS-82	09/23/76	1.145	85.0	1.90	3.10	1.50	130.0	4.60	226.0
USGS-82	10/03/78	1.185	100.0	2.90	4.80	1.20	160.0	6.10	275.0
USGS-82	10/12/77	1.157	89.0	2.30	3.80	1.50	140.0	5.60	242.0
K7?	09/23/76	1.129	71.0	1.20	2.60	1.80	120.0	4.60	201.0
K4	10/02/78	1.195	110.0	4.80	9.30	0.99	170.0	6.70	302.0
K4	09/23/76	1.194	100.0	4.70	7.90	1.10	180.0	5.70	299.0
K4	10/11/77	1.195	100.0	5.00	8.00	1.10	170.0	6.30	290.0
USGS-81	10/12/77	1.154	75.0	1.60	2.80	1.50	130.0	4.20	215.0
USGS-81	10/03/78	1.190	110.0	2.00	0.36	1.30	170.0	5.00	289.0
USGS-81	09/23/76	1.186	100.0	1.90	3.80	1.30	170.0	4.10	281.0
USGS-2/BLM-60	09/24/76	1.187	100.0	4.90	7.50	1.10	170.0	5.70	289.0
USGS-96/BLM-59	09/24/76	1.204	110.0	3.00	6.40	1.30	190.0	4.30	315.0
USGS-79	09/21/76	1.161	110.0	4.00	6.60	1.20	150.0	4.10	276.0
USGS-108	09/28/76	1.194	93.0	8.50	12.00	0.91	180.0	7.10	302.0
USGS-113	09/28/76	1.180	88.0	6.90	11.00	1.10	160.0	6.50	274.0
USGS-114	09/28/76	1.184	100.0	4.00	6.30	1.20	170.0	5.70	287.0
USGS-21	09/24/76	1.192	100.0	5.30	8.00	1.10	180.0	5.80	300.0
USGS-27	09/27/76	1.195	110.0	4.10	7.60	1.10	180.0	5.10	308.0
USGS-27	10/12/77	1.196	110.0	4.40	7.30	1.10	180.0	5.60	308.0
USGS-27	10/02/78	1.199	110.0	4.20	7.90	1.10	180.0	5.90	309.0
USGS-64	09/22/76	1.156	88.0	1.90	3.60	1.20	150.0	4.50	249.0
USGS-67	09/22/76	1.195	110.0	4.40	8.00	1.10	180.0	5.40	309.0
USGS-84	09/23/76	1.186	100.0	2.90	5.10	1.30	170.0	5.20	285.0
USGS-84	10/12/77	1.183	100.0	2.80	4.80	1.30	160.0	6.10	275.0
USGS-84	10/03/78	1.184	96.0	2.80	5.10	1.30	160.0	6.30	270.0
USGS-86	09/23/76	1.205	110.0	3.40	5.70	1.10	190.0	5.50	316.0
Mean		1.189	103.6	3.59	6.23	1.23	172.3	5.33	292.5
Minimum		1.129	71.0	0.96	0.36	0.91	120.0	3.80	201.0
Maximum		1.205	120.0	8.50	12.00	1.80	200.0	7.10	332.0

Table A1.3. Summary of 10 "K" BSF monitoring-well brine samples (Lines, 1978; Lines, 1979); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
K10	09/23/76	1.194	100.0	5.20	7.90	1.00	180.0	6.30	300.0
K10	10/03/78	1.188	94.0	4.80	7.50	1.00	160.0	7.00	274.0
K10	10/12/77	1.190	93.0	5.40	7.50	0.99	160.0	7.10	274.0
K46	09/28/76	1.175	95.0	2.10	4.20	1.40	160.0	4.50	267.0
K65	10/13/77	1.127	72.0	0.86	1.80	1.30	120.0	3.70	200.0
K65	09/28/76	1.125	70.0	0.98	1.90	1.20	110.0	3.60	188.0
K65	10/04/78	1.128	70.0	0.82	2.10	1.20	110.0	4.10	188.0
K66	10/04/78	1.178	99.0	2.20	4.90	1.30	160.0	5.70	273.0
K66	09/28/76	1.182	100.0	2.60	4.70	1.30	170.0	5.00	284.0
K66	10/13/77	1.181	100.0	2.70	4.40	1.40	170.0	5.50	284.0
Mean		1.167	89.3	2.77	4.69	1.21	150.0	5.25	253.2
Minimum		1.125	70.0	0.82	1.80	0.99	110.0	3.60	188.0
Maximum		1.194	100.0	5.40	7.90	1.40	180.0	7.10	300.0

Table A1.4. Summary of 34 "B" BSF auger-hole sample analyses (data file provided by J.L. Mason, Hydrologist, USGS, written communication, March 7, 2001); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
B1	05/11/81	1.195	93.0	4.40	7.60	1.20	180.0	5.80	292.0
B10	05/14/81	1.115	80.0	0.93	1.00	1.10	110.0	4.30	197.0
B11	05/14/81	1.147	90.0	1.80	1.10	1.10	130.0	5.90	230.0
B12	05/14/81	1.149	70.0	1.20	2.30	1.20	130.0	5.10	210.0
B13	05/14/81	1.167	85.0	1.40	2.50	1.40	150.0	5.10	245.0
B14	05/14/8	1.164	80.0	1.60	1.70	1.20	140.0	5.40	230.0
B15	05/14/81	1.173	90.0	1.40	1.70	1.50	140.0	6.90	242.0
B16	05/14/81	1.169	90.0	1.90	1.90	1.60	150.0	5.30	251.0
B17	05/15/81	1.177	87.0	1.70	2.90	1.40	150.0	5.20	248.0
B18	05/15/81	1.210	120.0	8.10	9.00	0.90	200.0	5.30	343.0
B19	05/19/81	1.188	100.0	3.20	2.80	1.30	150.0	4.80	262.0
B2	05/11/81	1.209	100.0	2.70	4.10	1.30	180.0	5.20	293.0
B20	05/19/81	1.178	96.0	2.30	1.60	1.40	160.0	5.20	267.0
B21	05/19/81	1.204	100.0	4.00	6.30	1.20	190.0	4.50	306.0
B22	05/20/81	1.197	110.0	2.90	3.40	1.40	190.0	4.90	313.0
B23	05/20/81	1.202	110.0	3.80	2.20	1.20	180.0	5.70	303.0
B24	05/20/81	1.206	100.0	4.80	7.60	1.20	190.0	5.60	309.0
B25	05/20/81	1.221	110.0	3.40	2.10	1.30	200.0	0.43	317.0
B26	05/21/81	1.190	110.0	3.20	3.90	1.30	180.0	5.10	304.0
B27	05/21/81	1.194	97.0	2.30	4.60	1.30	170.0	5.30	281.0
B28	05/21/81	1.202	110.0	3.80	2.40	1.20	180.0	2.90	300.0
B29	05/21/81	1.196	100.0	3.00	4.80	1.40	180.0	5.20	294.0
B3	05/12/81	1.169	87.0	1.50	2.90	1.40	150.0	4.30	247.0
B30	05/22/81	1.190	89.0	4.10	6.60	1.00	150.0	5.30	256.0
B31	05/22/81	1.216	110.0	1.10	2.80	1.20	200.0	3.80	319.0
B32	05/28/81	1.214	160.0	1.50	2.00	1.30	240.0	3.60	408.0
B33	05/28/81	1.192	90.0	3.70	5.60	1.20	160.0	6.00	267.0
B4	05/12/81	1.196	91.0	7.40	11.00	0.85	180.0	7.10	297.0
B5	05/13/81	1.196	100.0	5.50	5.30	0.91	180.0	7.30	299.0
B6	05/13/81	1.177	90.0	2.00	2.10	1.50	160.0	5.40	261.0
B7	05/13/81	1.166	90.0	2.70	2.00	1.30	150.0	6.90	253.0
B8	05/13/81	1.161	81.0	1.70	2.30	1.30	140.0	5.80	232.0
B9	05/14/81	1.128	70.0	1.00	1.50	1.50	120.0	4.50	199.0
BR1	05/20/81	1.216	110.0	3.30	4.80	1.20	200.0	5.00	324.0
Mean		1.185	96.9	2.92	3.72	1.26	166.5	5.12	276.4
Minimum		1.115	70.0	0.93	1.00	0.85	110.0	0.43	197.0
Maximum		1.221	160.0	8.10	11.00	1.60	240.0	7.30	408.0

Table A1.5. Summary of 17 "K" BSF monitoring-well sample analyses (data file provided by J.L. Mason, Hydrologist, USGS, written communication, March 7, 2001); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
K10-A	05/20/81	1.213	100.0	5.50	4.00	1.10	180.0	6.90	298.0
K11	05/20/81	1.215	100.0	4.70	3.60	1.10	180.0	5.40	295.0
K13	05/21/81	1.114	50.0	2.40	3.50	1.50	96.0	5.80	159.0
K15	05/19/81	1.183	100.0	3.70	3.30	1.30	160.0	4.90	273.0
K16	05/21/81	1.177	90.0	4.70	4.00	1.20	150.0	5.80	256.0
K19	05/19/81	1.197	110.0	2.20	2.40	1.30	190.0	4.50	310.0
K22	05/19/81	1.194	110.0	2.60	3.10	1.40	170.0	4.30	291.0
K24-A	05/19/81	1.194	100.0	4.80	5.00	1.10	180.0	6.10	297.0
K25	05/19/81	1.201	110.0	2.30	2.60	1.40	180.0	4.10	300.0
K26	05/20/81	1.199	110.0	6.10	4.10	0.96	190.0	6.10	317.0
K46	05/12/81	1.192	96.0	2.20	3.70	1.70	170.0	4.70	278.0
K5	05/19/81	1.212	100.0	5.00	2.00	1.00	180.0	6.80	295.0
K6	05/19/81	1.167	100.0	2.80	2.90	1.50	150.0	5.30	263.0
K65	05/14/81	1.132	100.0	0.86	1.00	1.10	140.0	3.80	247.0
K66	05/13/81	1.189	100.0	2.50	3.30	1.30	170.0	5.20	282.0
K75	05/28/81	1.205	110.0	3.60	6.40	1.20	190.0	5.10	316.0
K8-B	05/19/81	1.207	120.0	2.10	1.50	1.30	200.0	4.30	329.0
Mean		1.188	100.4	3.42	3.32	1.26	169.2	5.24	282.7
Minimum		1.114	50.0	0.86	1.00	0.96	96.0	3.80	159.0
Maximum		1.215	120.0	6.10	6.40	1.70	200.0	6.90	329.0

Table A1.6. Summary of 18 "L" BSF auger-hole sample analyses (data file provided by J.L. Mason, Hydrologist, USGS, written communication, March 7, 2001); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
L105	05/12/81	1.173	100.0	1.50	2.50	1.40	150.0	3.90	259.0
L106	05/12/81	1.194	94.0	3.70	8.10	1.20	170.0	5.40	282.0
L109	05/14/81	1.157	78.0	1.10	2.10	1.30	140.0	4.80	227.0
L17	05/20/81	1.204	120.0	3.20	2.80	1.20	200.0	4.60	332.0
L27	05/28/81	1.213	110.0	3.90	6.60	1.20	190.0	4.80	317.0
L29	05/28/81	1.202	110.0	0.85	1.90	1.20	200.0	3.80	318.0
L33	05/22/81	1.212	100.0	5.20	2.30	1.10	190.0	5.60	304.0
L35	05/22/81	1.206	110.0	5.30	4.90	1.20	190.0	5.30	317.0
L37	05/22/81	1.205	100.0	7.10	7.70	1.10	180.0	5.90	302.0
L38	05/22/81	1.204	100.0	3.70	7.50	1.10	190.0	5.10	307.0
L52	05/12/81	1.166	79.0	1.70	3.10	1.40	140.0	5.40	231.0
L53	05/15/81	1.191	100.0	2.30	2.10	1.30	170.0	4.90	281.0
L54	05/28/81	1.092	50.0	1.70	1.80	0.87	82.0	4.00	140.0
L58	05/12/81	1.191	100.0	4.80	6.70	1.20	170.0	5.50	288.0
L60	05/21/81	1.180	88.0	2.50	4.20	1.30	150.0	5.30	251.0
L73	05/20/81	1.201	110.0	3.80	3.70	1.20	190.0	5.50	314.0
L74	05/22/81	1.205	100.0	1.70	8.00	1.30	180.0	6.00	297.0
L79	05/19/81	1.203	100.0	4.40	4.40	1.20	180.0	5.60	296.0
Mean		1.189	97.2	3.25	4.47	1.21	170.1	5.08	281.3
Minimum		1.092	50.0	0.85	1.80	0.87	82.0	3.80	140.0
Maximum		1.213	120.0	7.10	8.10	1.40	200.0	6.00	332.0

Table A1.7. Summary of 26 BSF monitoring-well samples collected in 1992 by USGS (Mason and others, 1995) - see text table 9; cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
BLM-91	10/02/92	1.179	110.0	3.00	4.70	1.30	180.0	6.20	321
BLM-60/USGS-2	08/12/92	1.190	100.0	5.00	7.30	1.20	160.0	6.40	301
BLM-28	08/12/92	1.190	100.0	4.70	7.10	1.20	160.0	6.20	307
BLM-43C	08/12/92	1.200	110.0	3.70	7.10	1.10	160.0	5.40	318
BLM-44A	08/11/92	1.202	110.0	3.00	4.70	1.20	160.0	8.00	336
BLM-48/K-5	08/11/92	1.190	110.0	4.10	7.10	1.10	180.0	6.20	313
BLM-47	08/11/92	1.200	99.0	5.40	8.20	1.00	160.0	9.50	327
BLM-45	08/11/92	1.200	100.0	4.50	7.10	0.92	160.0	9.40	329
BLM-53	08/11/92	1.198	110.0	3.80	4.70	1.30	170.0	5.70	309
BLM-29/K-7	08/12/92	1.190	100.0	3.20	6.80	1.20	160.0	5.60	303
BLM-108	10/02/92	1.182	95.0	4.70	5.80	1.10	160.0	6.50	305
BLM-71A/USGS-9	08/25/92	1.190	98.0	5.40	10.00	0.94	170.0	9.30	329
BLM-93B	08/25/92	1.176	94.0	4.60	8.10	1.00	150.0	8.00	274
BLM-30C	08/25/92	1.186	100.0	4.40	7.60	1.10	160.0	6.70	292
BLM-103	10/02/92	1.180	92.0	4.80	3.50	1.10	150.0	6.10	302
BLM-20/USGS-64	08/25/92	1.160	89.0	1.90	3.50	1.20	140.0	7.50	262
BLM-41	08/25/92	1.192	100.0	4.30	7.30	0.94	170.0	6.40	323
BLM-2/B-27	08/26/92	1.170	100.0	1.80	4.30	1.10	150.0	5.50	285
BLM-95	10/02/92	1.148	79.0	1.40	2.30	1.60	120.0	5.60	236
BLM-65/USGS-74	08/25/92	1.190	100.0	5.20	9.60	1.00	160.0	6.20	312
BLM-6/USGS-37	08/26/92	1.190	100.0	5.60	9.50	1.00	160.0	6.40	315
BLM-16/USGS-34	08/26/92	1.194	100.0	4.80	9.10	1.00	170.0	8.50	329
BLM-36A/USGS-31	08/26/92	1.190	120.0	1.80	4.60	1.20	170.0	4.50	340
BLM-36/USGS-32	08/26/92	1.200	120.0	3.40	7.90	1.20	170.0	4.90	325
BLM-124	10/02/92	1.120	110.0	4.60	8.50	1.10	160.0	5.40	310
BLM-14/USGS-27	08/26/92	1.200	110.0	3.10	6.80	1.10	140.0	7.90	336
Mean		1.185	102.2	3.93	6.66	1.12	159.6	6.69	309
Minimum		1.120	79.0	1.40	2.30	0.92	120.0	4.50	236
Maximum		1.202	120.0	5.60	10.00	1.60	180.0	9.50	340

Table A1.8. Summary of 20 BSF monitoring-well samples collected in 1993 by USGS (Mason and others, 1995) - see text table 9; cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Date	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
BLM-60/USGS-2	07/13/93	1.180	99.0	3.80	6.20	0.97	172.0	6.00	300
BLM-28	07/01/93	1.180	98.0	2.20	5.70	2.10	170.0	5.90	283
BLM-44A	06/23/93	1.200	110.0	2.50	4.20	1.10	160.0	4.20	288
BLM-47	06/23/93	1.190	100.0	4.30	6.70	0.97	160.0	6.30	319
BLM-53	06/23/93	1.170	97.0	3.20	5.00	1.30	150.0	4.70	294
BLM-29/K-7	06/23/93	1.180	100.0	3.20	4.30	1.20	160.0	4.80	298
BLM-108	06/23/93	1.180	100.0	3.20	4.30	1.20	160.0	4.80	298
BLM-71A/USGS-9	07/13/93	1.190	103.0	4.80	8.30	0.83	186.0	6.90	318
BLM-93	09/01/93	1.180	100.0	5.80	8.10	1.10	170.0	7.50	292
BLM-93B	09/01/93	1.170	81.0	4.50	4.10	1.00	140.0	7.80	261
BLM-93C	09/01/93	1.190	110.0	3.90	3.80	1.10	180.0	5.10	320
BLM-30C	06/24/93	1.170	98.0	4.20	6.10	1.00	150.0	6.30	297
BLM-103	06/23/93	1.170	100.0	3.00	4.30	1.10	150.0	6.80	284
BLM-20/USGS-64	06/03/93	1.160	81.0	1.80	3.90	1.10	120.0	3.30	244
BLM-41	06/24/93	1.180	98.0	4.70	7.20	1.00	140.0	6.40	309
BLM-2/B-27	06/08/93	1.170	100.0	2.20	4.40	1.40	150.0	4.80	278
BLM-65/USGS-74	07/07/93	1.180	92.0	5.00	0.72	0.97	180.0	5.60	306
BLM-6/USGS-37	07/13/93	1.190	102.0	5.10	8.50	0.96	185.0	6.40	313
BLM-36/USGS-32	07/14/93	1.190	104.0	4.30	7.40	1.10	196.0	6.20	323
BLM-14/USGS-27	07/14/93	1.190	110.0	3.30	5.40	1.10	20.0	5.00	322
Mean		1.181	99.2	3.75	5.43	1.13	155.01	5.74	297
Minimum		1.160	81.0	1.80	0.72	0.83	20.0	3.30	244
Maximum		1.200	110.0	5.80	8.50	2.10	196.0	7.80	323

Table A1.9. Summary of 9 samples selected from the 26 BSF monitoring-well samples collected in 1992 by USGS (Mason and others, 1995); these selected samples were compared with BLM samples collected from the same wells during 1994-1997 (see text table 13); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
BLM-6	1.196	100.00	5.60	9.50	1.00	160.00	6.40	315.00
BLM-28	1.194	100.00	4.70	7.10	1.20	160.00	6.20	307.00
BLM-41	1.192	100.00	4.30	7.30	0.94	170.00	6.40	323.00
BLM-43C	1.200	110.00	3.70	7.10	1.10	160.00	5.40	318.00
BLM-50A	1.194	100.00	4.30	6.80	1.20	170.00	5.90	309.00
BLM-53	1.198	110.00	3.80	4.70	1.30	170.00	5.70	309.00
BLM-60	1.192	100.00	5.00	7.30	1.20	160.00	6.40	301.00
BLM-71A	1.198	98.00	5.40	10.00	0.94	170.00	9.30	329.00
BLM-93	1.182	100.00	5.80	8.10	1.10	170.00	7.50	292.00
Mean	1.194	102.00	4.73	7.54	1.11	165.56	6.58	311.44
Miniumum	1.182	98.00	3.70	4.70	0.94	160.00	5.40	292.00
Maximum	1.200	110.00	5.80	10.00	1.30	170.00	9.30	329.00

Table A1.10. Summary of 9 samples selected from the 20 BSF monitoring-well samples collected in 1993 by USGS (Mason and others, 1995); these selected samples were compared with BLM samples collected from the same wells during 1994-1997 (see text table 13); cation/anion values expressed as g/L; density expressed as g/mL.

Sample	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS
BLM-6	1.192	102.00	5.10	8.50	0.96	185.00	6.40	313.00
BLM-28	1.188	98.00	2.20	5.70	2.10	170.00	5.90	283.90
BLM-41	1.188	98.00	4.70	7.20	1.00	140.00	6.40	309.00
BLM-43C	1.200	110.00	2.50	4.20	1.10	160.00	4.20	288.00
BLM-53	1.174	97.00	3.20	5.00	1.30	150.00	4.70	294.00
BLM-60	1.184	99.00	3.80	6.20	0.97	172.00	6.00	300.00
BLM-71A	1.192	103.00	4.80	8.30	0.83	186.00	6.90	318.00
BLM-93	1.182	100.00	5.80	8.10	1.10	170.00	7.50	292.50
BLM-100	1.174	100.00	3.00	4.30	1.10	150.00	6.80	284.00
Mean	1.186	100.78	3.90	6.39	1.16	164.78	6.09	298.04
Minimum	1.174	97.00	2.20	4.20	0.83	140.00	4.20	283.90
Maximum	1.200	110.00	5.80	8.50	2.10	186.00	7.50	318.00

APPENDIX A2

1994-2000 BSF MONITORING-WELL SAMPLE ANALYSES BY BLM

Table A2.1. Summary of 19 FY94 BSF monitoring-well brine samples collected by BLM September 19-20, 1994 (concentrations expressed as g/L; density expressed as g/mL)

Sample	Density	Na	Mg	K	Ca[1]	Cl	SO4	TDS	mole bal.[2]
94BLM-3	1.174	95.2	2.70	3.80	1.10	156.7	5.02	264.5	-0.000498
94BLM-6	1.200	99.3	8.50	9.40	0.86	185.4	5.79	309.3	-0.002045
94BLM-12	1.205	116.9	4.20	5.70	0.90	192.5	4.34	324.5	0.003956
94BLM-25	1.193	98.3	5.60	6.20	0.80	173.3	5.59	289.8	-0.002644
94BLM-30	1.177	96.1	3.30	3.80	1.10	160.3	5.11	269.7	-0.001187
94BLM-35	1.177	95.8	3.00	4.30	1.10	159.5	5.02	268.7	-0.001196
94BLM-41	1.198	100.5	6.80	7.30	0.70	181.2	5.18	301.7	-0.002410
94BLM-43C	1.202	111.7	5.30	6.40	0.70	186.8	4.83	315.7	0.005418
94BLM-46	1.204	112.6	7.60	8.30	0.60	195.8	5.31	330.2	0.005817
94BLM-50A	1.199	110.6	4.80	5.50	0.80	186.8	5.02	313.5	0.000596
94BLM-53	1.192	111.2	5.10	5.80	0.80	184.7	4.83	312.4	0.005734
94BLM-61	1.201	111.6	6.00	7.70	0.70	189.8	5.12	320.9	0.005203
94BLM-82	1.195	111.3	4.10	5.50	0.86	185.4	4.92	311.9	0.001223
94BLM-99	1.166	88.9	6.10	5.80	0.60	152.6	6.01	260.0	0.006078
94BLM-101	1.188	97.2	5.60	5.40	1.40	169.9	5.70	285.2	-0.001537
94BLM-107	1.188	97.4	5.30	5.90	0.90	169.5	5.58	284.6	-0.001086
94BLM-60	1.193	98.5	5.90	7.30	0.70	174.8	5.59	292.8	-0.001862
94BLM-71/USGS-9	1.200	100.4	7.50	9.30	0.86	184.4	6.08	308.4	-0.002647
94BLM-28	1.196	100.5	6.10	6.60	0.86	178.5	5.49	297.9	-0.002615
Mean	1.192	102.8	5.45	6.32	0.89	177.3	5.29	298.1	0.002830
Minimum	1.166	88.9	2.70	3.80	0.76	152.6	4.34	260.5	-0.002647
Maximum	1.205	116.9	8.50	9.40	1.08	195.8	6.08	330.4	0.006078

[1]Because Ca was not included in 1994 analyses, either matching or average (0.86) 1996 Ca values were used.
[2]Because of the occurrence of negative values, the mole-balance mean was calculated by converting sample mole balances to absolute values; this was done to avoid the possibility of a zero mean value.

Table A2.2. Summary of 13 FY95 BSF monitoring-well brine samples collected by BLM in September 1995 (concentrations expressed as g/L; density expressed as g/mL).

Sample ID	Density	Na	Mg	K	Ca1	Cl	SO4	TDS	mole bal.[2]
95BLM-3	1.170	92.7	2.90	3.70	1.05	144.2	5.47	249.0	0.010124
95BLM-6	1.201	97.4	7.25	9.00	1.05	170.3	5.78	289.7	0.008002
95BLM-12	1.205	106.6	3.89	5.40	1.05	169.8	4.50	290.2	0.010979
95BLM-19	1.198	107.2	2.95	3.60	1.05	170.3	3.99	288.0	0.006837
95BLM-25	1.195	99.5	4.97	5.90	1.05	165.8	5.38	281.6	0.006356
95BLM-28	1.195	100.4	4.97	5.90	1.05	163.7	5.13	280.1	0.010750
95BLM-43C	1.200	105.9	4.89	6.00	1.05	172.3	4.23	293.3	0.011120
95BLM-46	1.206	107.3	6.30	7.70	1.05	179.6	5.30	306.2	0.010742
95BLM-50A	1.194	102.9	3.93	5.50	1.05	164.5	4.81	281.6	0.010575
95BLM-53	1.194	104.6	4.25	5.60	1.05	168.5	5.01	288.0	0.009983
95BLM-60	1.193	98.7	4.83	7.20	1.05	161.3	5.77	277.8	0.010799
95BLM-61	1.205	107.4	4.80	6.60	1.05	174.6	4.90	298.3	0.010840
95BLM-82	1.196	104.3	3.85	5.30	1.05	165.9	4.84	284.2	0.010938
Mean	1.196	102.7	4.60	5.95		167.0	5.01	285.2	0.009850
Minimum	1.170	92.7	2.90	3.60		144.2	3.99	249.0	0.006356
Maximum	1.206	107.4	7.25	9.00		179.6	5.78	306.2	0.011120

[1]Calcium was not analyzed; values are averages of USGS FY92-FY93, and BLM FY96-FY97 calcium analyses.

Table A2.3. Summary of 16 FY96 BSF monitoring-well brine samples collected by BLM September 24, 1996 (concentrations expressed as g/L; density expressed as g/mL)

Sample	Density	Na	Mg	K	Ca	Cl	SO4	TDS	mole bal.[2]
96BLM-3	1.171	93.1	1.90	4.00	1.10	149.4	4.85	254.3	0.002029
96BLM-12	1.204	116.5	2.80	6.00	0.90	190.8	4.20	321.2	0.001129
96BLM-25	1.187	95.4	3.40	5.90	0.80	163.8	5.10	274.4	-0.004556
96BLM-30	1.174	94.9	1.60	3.55	1.10	157.0	4.45	262.5	-0.004958
96BLM-35	1.179	96.6	1.80	3.90	1.10	156.6	4.10	264.1	0.000157
96BLM-41	1.196	98.6	4.70	8.10	0.70	176.2	5.15	293.4	-0.006752
96BLM-43C	1.201	103.3	3.60	6.90	0.70	178.2	4.45	297.1	-0.005000
96BLM-46	1.206	99.6	5.20	8.45	0.60	179.8	4.80	298.4	-0.006930
96BLM-50A	1.194	97.3	3.60	5.90	0.80	168.2	4.70	280.5	-0.005077
96BLM-53	1.194	101.5	3.55	5.55	0.80	175.2	4.45	291.1	-0.006083
96BLM-61	1.208	101.9	4.80	8.45	0.70	180.8	4.45	301.1	-0.004799
96BLM-93	1.189	92.8	3.80	8.10	0.80	157.0	6.45	269.0	0.001421
96BLM-99	1.159	91.6	4.90	5.35	0.60	158.7	6.60	267.8	-0.002557
96BLM-101	1.076	37.8	0.90	2.20	1.40	60.9	4.85	108.1	0.001194
96BLM-107	1.184	93.9	3.50	6.10	0.90	160.8	5.00	270.2	-0.002887
96BLM-60	1.193	96.2	4.30	8.45	0.70	170.7	5.30	285.6	-0.005627
Mean	1.182	94.4	3.40	6.06	0.86	161.5	4.93	271.1	0.003820
Minimum	1.076	37.8	0.90	2.20	0.60	60.9	4.10	108.1	-0.006930
Maximum	1.208	116.5	5.20	8.45	1.40	190.8	6.60	321.2	0.002029

[2]Because of the occurrence of negative values, the mole-balance mean was calculated by converting sample mole balances to absolute values; this was done to avoid the possibility of a zero mean value.

Table A2.4. Summary of 20 BSF FY97 monitoring-well brine samples collected by BLM September 23-24, 1997 (concentrations expressed as g/L; density expressed as g/mL).

Sample	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS	mole bal.[2]
97BLM-6	1.197	93.9	4.70	9.00	0.88	162.9	5.70	277.1	0.001333
97BLM-3	1.162	84.4	1.45	3.55	1.50	137.0	5.25	233.2	-0.000744
97BLM-12	1.202	97.0	1.25	5.90	1.04	156.9	4.80	266.9	-0.000019
97BLM-25	1.188	93.1	3.15	6.05	1.02	155.2	5.95	264.5	0.000551
97BLM-27	1.112	48.4	0.55	1.90	1.47	76.0	4.95	133.3	0.001161
97BLM-30	1.173	92.7	1.00	3.30	1.54	149.9	4.90	253.3	-0.002313
97BLM-41	1.197	94.3	2.85	6.25	0.90	156.6	5.95	266.9	0.000010
97BLM-43C	1.201	97.6	3.00	6.00	1.05	162.9	4.80	275.4	0.000144
97BLM-46	1.207	96.4	2.80	6.50	0.85	158.2	5.80	270.6	0.002045
97BLM-50B	1.197	98.7	3.20	5.55	1.10	166.4	5.30	280.3	-0.002104
97BLM-53	1.196	96.8	2.45	5.00	1.15	156.3	5.15	266.9	0.003416
97BLM-60	1.195	94.5	4.05	6.55	1.05	162.2	5.90	274.3	-0.001425
97BLM-61	1.204	94.6	3.70	6.80	0.95	158.2	5.85	270.1	0.002357
97BLM-82	1.198	97.6	2.55	4.90	1.15	162.5	4.85	273.6	-0.001939
97BLM-90	1.17	86.8	1.45	2.65	1.15	138.8	4.15	235.0	0.000801
97BLM-93	1.191	94.5	4.55	7.00	0.95	162.8	7.86	277.7	0.001853
97BLM-99	1.164	76.0	2.25	4.20	1.05	122.6	7.10	213.2	0.001931
97BLM-100	1.189	96.3	3.85	5.55	1.05	159.8	6.60	273.2	0.002326
97BLM-107	1.183	90.1	2.45	4.50	1.10	147.0	6.00	251.2	0.000828
97BLM-107A	1.177	94.5	1.60	3.80	1.50	154.2	5.30	260.9	-0.001929
Mean	1.185	90.9	2.64	5.25	1.12	150.3	5.61	255.9	0.001460
Minimum	1.112	48.4	0.55	1.90	0.85	76.0	4.15	133.3	-0.002310
Maximum	1.207	98.7	4.70	9.00	1.54	166.4	7.86	280.3	0.003416

Table A2.5. Summary of 10 FY2K BSF monitoring-well brine samples collected by BLM October 1, 1999 (cation/anion values expressed as g/L; density expressed as g/mL).

Sample	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS	mole bal.[2]
2KBLM-3	1.165	82.2	2.49	3.50	1.51	139.4	4.77	233.8	-0.003756
2KBLM-27	1.191	93.6	2.94	5.34	1.24	159.4	4.77	267.3	-0.003524
2KBLM-30	1.147	76.0	1.31	1.89	1.68	125.6	4.44	210.9	-0.003962
2KBLM-35	1.173	87.4	1.54	3.19	1.47	143.2	4.33	241.1	-0.001966
2KBLM-41	1.196	93.1	4.12	6.74	1.11	162.0	5.23	272.3	-0.002660
2KBLM-50B	1.197	96.2	2.94	5.70	1.08	164.0	6.07	276.0	-0.005269
2KBLM-53	1.186	91.6	2.77	5.06	1.18	155.6	4.71	260.9	-0.003653
2KBLM-56	1.186	93.1	2.12	4.59	1.30	155.2	4.74	261.0	-0.003023
2KBLM-90	1.121	61.8	1.71	1.89	1.50	100.7	4.46	172.1	0.000851
2KBLM-107	1.171	84.4	2.79	5.06	1.23	143.8	5.32	242.6	-0.003165
Mean	1.173	85.9	2.47	4.30	1.33	144.9	4.88	243.8	0.003180
Minimum	1.121	61.8	1.31	1.89	1.08	100.7	4.33	172.1	-0.005270
Maximum	1.197	96.2	4.12	6.74	1.68	164.0	6.07	276.0	0.000851

[2]Because of the occurrence of negative values, the mole-balance mean was calculated by converting sample mole balances to absolute values; this was done to avoid the possibility of a zero mean value.

APPENDIX A3

FY98-FY2K LAYDOWN-BRINE SAMPLE ANALYSES BY BLM

Table A3.1. Summary of 9 BLM laydown-brine analyses from FY98A sampling (concentration expressed as g/L; density expressed as g/mL).

Sample	Date	Location	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS	mole bal[1]
FY98A B-1	15Jan98	BP#3	1.064	34.4	0.12	0.20	0.59	52.8	1.40	89.5	0.001050
FY98A B-2	15Jan98	LDM-W	1.065	33.5	0.09	0.20	0.48	51.1	1.20	86.6	0.001285
FY98A B-3	15Jan98	LDM-E	1.057	33.5	0.14	0.20	0.71	48.9	1.75	85.2	0.004492
FY98A B-4	23Jan98	BP#3	1.082	43.6	0.11	0.25	0.64	67.8	1.60	114.0	-0.000082
FY98A B-5	23Jan98	PP#4	1.051	28.2	0.11	0.20	0.57	41.7	1.40	72.1	0.003108
FY98A B-6	23Jan98	LDM-W	1.080	41.5	0.11	0.25	0.63	65.1	1.50	109.0	-0.000646
FY98A B-7	23Jan98	LDM-E	1.043	23.3	0.09	0.20	0.59	35.2	1.40	60.7	0.001672
FY98A B-8	26Jan98	LDM-E	1.041	19.5	0.11	0.20	0.64	28.2	1.40	50.0	0.003419
FY98A B-9	26Jan98	LDM-W	1.041	20.2	0.18	0.20	0.80	30.9	1.95	54.2	0.001266
Mean			1.058	30.9	0.12	0.21	0.63	46.8	1.51	80.2	0.001891
Minimum			1.041	19.5	0.09	0.20	0.48	28.2	1.20	50.0	-0.000650
Maximum			1.082	43.6	0.18	0.25	0.80	67.8	1.95	114.0	0.004492

Table A3.2. Summary of 8 BLM laydown-brine analyses from FY98B sampling (concentration expressed as g/L; density expressed as g/mL).

Sample	Date	Location	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS	mole bal[1]
FY98B B-12	2Mar98	LDM-E	1.179	102.9	0.25	0.29	1.35	167.7	2.35	274.8	-0.008809
FY98B B-13	10Mar98	LDM-W	1.159	91.5	0.20	0.29	1.07	148.4	2.49	244.0	-0.007775
FY98B B-15	10Mar98	BP#3	1.158	92.0	0.20	0.29	0.95	149.4	2.57	245.4	-0.008485
FY98B B-16	27Mar98	BP#3	1.156	89.0	0.20	0.29	1.13	142.1	2.93	235.6	-0.005174
FY98B B-17	27Mar98	LDM-W	1.159	87.5	0.17	0.29	1.14	141.5	3.23	233.8	-0.007506
FY98B B-19	9Apr98	LDM-W	1.041	19.2	0.16	0.29	0.59	32.9	2.10	55.2	-0.004155
FY98B B-21	9Apr98	BP#3	1.040	21.4	0.17	0.35	0.77	35.5	2.17	60.4	-0.002609
FY98B B-22	22Apr98	BP#3	1.149	78.1	0.25	0.45	0.90	128.0	2.24	209.9	-0.008049
Mean			1.130	72.7	0.20	0.32	0.99	118.2	2.51	194.9	-0.006570
Minimum			1.040	19.2	0.16	0.29	0.59	32.9	2.10	55.2	-0.008810
Maximum			1.179	102.9	0.25	0.45	1.35	167.7	3.23	274.8	-0.002610

[1]Because of the occurrence of negative values, the mole-balance mean was calculated by converting sample mole balances to absolute values; this was done to avoid the possibility of a zero mean value.

Table A3.3. Summary of 29 BLM Laydown-brine analyses from FY99 sampling (concentration expressed as g/L; density expressed as g/mL).

Sample	Date	Location	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS	mole bal[1]
FY99 B-25	6Nov98	BP#3	1.180	97.5	0.24	0.25	1.25	156.7	2.86	258.8	-0.006348
FY99 B-26	6Nov98	LDM-W	1.180	97.1	0.23	0.20	1.25	155.3	2.93	257.0	-0.005563
FY99 B-27	6Nov98	LDM-E	1.198	100.9	0.29	0.30	1.40	161.4	3.30	267.6	-0.005458
FY99 B-28	17Nov98	LDM-W	1.196	102.6	0.25	0.25	1.36	162.3	2.98	269.7	-0.003433
FY99 B-29	17Nov98	LDM-E	1.198	102.7	0.24	0.20	1.37	162.8	3.10	270.4	-0.004005
FY99 B-30	17Nov98	BP#3	1.193	100.9	0.25	0.30	1.36	162.2	2.93	267.9	-0.006325
FY99 B-31	3Dec98	BP#3	1.193	99.6	0.28	0.35	1.34	160.5	2.95	265.0	-0.006588
FY99 B-32	3Dec98	LDM-W	1.194	100.1	0.28	0.25	1.34	161.4	2.85	266.2	-0.006754
FY99 B-33	3Dec98	LDM-E	1.194	101.0	0.27	0.35	1.35	162.1	2.82	267.9	-0.005822
FY99 B-34	14Jan99	LDM-W	1.183	99.8	0.29	0.30	1.31	158.2	2.90	262.8	-0.003572
FY99 B-35	14Jan99	LDM-E	1.182	98.9	0.31	0.30	1.30	157.1	3.02	260.9	-0.003976
FY99 B-36	14Jan99	BP#3	1.182	99.2	0.29	0.25	1.27	156.5	2.86	260.4	-0.002754
FY99 B-37	22Jan99	LDM-W	1.155	86.8	0.32	0.40	1.18	136.0	2.66	227.4	-0.000878
FY99 B-38	22Jan99	LDM-E	1.182	199.6	0.33	0.40	1.34	160.4	2.84	264.9	-0.006205
FY99 B-39	22Jan99	BP#3	1.157	87.8	0.33	0.35	1.19	140.9	2.63	233.2	-0.004941
FY99 B-40	19Feb99	LDM-W	1.184	99.5	0.36	0.45	1.39	159.7	2.95	264.4	-0.005377
FY99 B-41	19Feb99	LDM-E	1.187	100.7	0.39	0.50	1.42	162.6	3.12	268.7	-0.006538
FY99 B-42	19Feb99	BP#3	1.183	100.6	0.39	0.45	1.39	162.2	3.05	268.1	-0.006323
FY99 B-43	25Feb99	BP#3	1.189	100.8	0.39	0.50	1.40	162.4	2.92	268.4	-0.005974
FY99 B-44	25Feb99	LDM-W	1.190	101.0	0.39	0.45	1.40	162.5	2.93	268.7	-0.005785
FY99 B-45	25Feb99	LDM-E	1.190	101.9	0.35	0.40	1.43	162.8	3.04	269.9	-0.004721
FY99 B-49	12Mar99	LDM-E	1.179	97.8	0.34	0.45	1.38	155.7	3.05	258.7	-0.003930
FY99 B-50	12Mar99	LDM-W	1.166	92.7	0.33	0.40	1.30	145.0	2.99	242.7	-0.000753
FY99 B-51	12Mar99	BP#3	1.164	90.5	0.32	0.35	1.29	143.4	2.91	238.8	-0.002967
FY99 B-52	19Apr99	BP#3	1.195	100.9	0.35	0.40	1.45	162.0	3.16	268.3	-0.005639
FY99 B-53	19Apr99	LDM-W	1.195	101.5	0.35	0.35	1.45	161.5	3.25	268.4	-0.004089
FY99 B-55	20Apr99	LDM-E	1.197	101.8	0.32	0.40	1.46	162.8	3.05	269.8	-0.004924
Mean			1.185	98.7	0.31	0.35	1.35	157.6	2.96	261.3	-0.004801
Minimum			1.155	86.8	0.23	0.20	1.18	136.0	2.63	227.4	-0.006750
Maximum			1.198	102.7	0.39	0.50	1.46	162.8	3.30	270.4	-0.000750

[1]Because of the occurrence of negative values, the mole-balance mean was calculated by converting sample mole balances to absolute values; this was done to avoid the possibility of a zero mean value.

Table A3.4. Summary of 30 BLM Laydown-brine analyses from FY2K sampling (concentration expressed as g/L; density expressed as g/mL).

Sample	Date	Location	Density	Na	Mg	K	Ca	Cl	SO$_4$	TDS	mole bal[1]
FY2KB-56	9Nov99	BP#3	1.185	110.0	0.25	0.46	1.41	172.5	2.85	287.5	-0.001502
FY2KB-57	9Nov99	LDM-W	1.187	114.1	0.04	0.46	1.47	175.3	2.84	294.2	0.002067
FY2KB-58	9Nov99	LDM-E	1.199	116.9	0.46	0.77	1.43	182.2	3.41	305.1	0.000203
FY2KB-59	30Nov99	BP#3	1.167	99.5	0.04	0.31	1.50	155.9	3.11	260.4	-0.002101
FY2KB-60	30Nov99	LDM-W	1.168	101.8	0.14	0.31	1.28	154.6	3.62	261.7	0.003278
FY2KB-61	30Nov99	LDM-E	1.174	101.4	0.12	0.31	1.33	158.7	2.87	264.7	-0.001752
FY2KB-62	14Dec99	BP#3	1.163	98.2	0.47	0.38	1.31	157.8	2.84	261.0	-0.005411
FY2KB-63	14Dec99	LDM-W	1.163	96.8	0.68	0.38	1.41	146.3	3.29	248.8	0.006544
FY2KB-64	14Dec99	LDM-E	1.168	98.4	0.51	0.38	1.34	149.0	2.93	252.6	0.005735
FY2KB-65	29Dec99	BP#3	1.167	98.4	0.16	0.38	1.31	149.0	3.09	252.4	0.004300
FY2KB-66	29Dec99	LDM-W	1.167	100.1	0.05	0.38	1.31	151.8	3.09	256.7	0.003745
FY2KB-67	29Dec99	LDM-E	1.168	100.1	0.09	0.38	1.37	156.7	2.84	261.5	-0.001683
FY2KB-68	18Jan2K	BP#3	1.148	92.8	0.30	0.56	1.27	148.8	3.10	246.8	-0.005338
FY2KB-69	18Jan2K	LDM-W	1.146	92.8	0.30	0.56	1.27	149.0	2.98	247.0	-0.005534
FY2KB-70	18Jan2K	LDM-E	1.144	90.3	0.22	0.56	1.27	144.9	2.81	240.1	-0.005325
FY2KB-71	07Feb2K	LDM-E	1.117	71.3	0.41	0.65	1.07	117.3	2.20	192.9	-0.006677
FY2KB-72	07Feb2K	LDM-W	1.117	70.4	0.32	0.65	1.01	115.7	2.05	190.1	-0.006710
FY2KB-73	07Feb2K	BP#3	1.112	71.9	0.39	0.65	0.98	116.7	1.95	192.6	-0.004789
FY2KB-74	01Mar2K	LDM-E	1.141	89.6	0.42	0.74	1.27	146.0	2.95	241.0	-0.007288
FY2KB-75	01Mar2K	LDM-W	1.141	84.2	0.42	0.74	1.27	133.9	2.71	223.2	-0.002307
FY2KB-76	01Mar2K	BP#3	1.137	85.5	0.42	0.65	1.22	136.0	2.72	226.5	-0.002703
FY2KB-77	17Mar2K	BP#3	1.157	97.2	0.34	0.65	1.38	154.3	3.46	257.4	-0.003599
FY2KB-78	17Mar2K	LDM-W	1.156	97.2	0.24	0.56	1.42	153.2	3.15	255.8	-0.002301
FY2KB-79	17Mar2K	LDM-E	1.161	96.2	0.48	0.83	1.41	153.2	3.55	255.7	-0.003397
FY2KB-80	31Mar2K	LDM-E	1.197	120.0	0.18	0.56	1.52	189.6	3.24	315.1	-0.003757
FY2KB-81	31Mar2K	LDM-W	1.189	118.8	0.31	0.46	1.32	189.3	3.57	313.8	-0.006059
FY2KB-82	31Mar2K	BP#3	1.189	117.8	0.24	0.46	1.44	187.7	3.44	311.1	-0.005796
FY2KB-83	27Apr2K	LDM-E	1.194	117.8	0.22	0.46	1.40	188.4	2.85	311.2	-0.006308
FY2KB-84	27Apr2K	LDM-W	1.195	117.8	0.26	0.56	1.46	188.1	3.40	311.5	-0.005963
FY2KB-85	27Apr2K	BP#3	1.188	117.8	0.29	0.65	1.47	186.3	3.50	310.0	-0.003775
Mean			1.164	99.5	0.29	0.53	1.33	156.9	3.01	261.6	0.004198
Minimum			1.112	70.4	0.04	0.31	0.98	115.7	1.95	190.1	-0.000729
Maximum			1.199	120.0	0.68	0.83	1.52	189.6	3.62	315.1	0.006544

[1]Because of the occurrence of negative values, the mole-balance mean was calculated by converting sample mole balances to absolute values; this was done to avoid the possibility of a zero mean value.

APPENDIX A4

FY98-FY2K LAYDOWN-BRINE MONTHLY PRODUCTION SUMMARY

Table A4.1. FY98-FY2K monthly Laydown NaCl tonnage, pump hours, acre feet, and gallons.

Sample Months	NaCl, Tons (dry)	Pumped Brine		Hours Pumped Per Month		
		Acre Feet	Gallons	Maximum Possible	Actually Pumped	% of Possible
NOV 97	118,982	368	119,973,750	720	299	41.5
DEC 97	30,739	208	67,811,250	744	169	22.7
JAN 98	80,359	616	200,625,000	744	500	67.2
FEB 98	129,792	356	115,961,250	672	289	43.0
MAR 98	278,446	911	296,925,000	744	740	99.5
APR 98	186,888	702	228,712,500	720	570	79.2
NOV 98	336,510	872	284,085,000	720	708	98.3
DEC 98	347,383	916	298,530,000	744	744	100.0
JAN 99	322,864	916	298,530,000	744	744	100.0
FEB 99	286,451	828	269,640,000	744	744	100.0
MAR 99	332,375	916	298,530,000	744	744	100.0
APR 99	339,486	887	288,900,000	720	720	100.0
NOV 99	315,518	883	287,696,250	720	717	99.6
DEC 99	322,171	916	298,530,000	744	744	100.0
JAN 2K	269,879	916	298,530,000	744	744	100.0
FEB 2K	242,421	857	279,270,000	696	696	100.0
MAR 2K	332,938	916	298,530,000	744	744	100.0
APR 2K	350,147	856	278,868,750	720	695	96.5

APPENDIX A5

FY98-FY2K LAYDOWN-BRINE Na & Cl ANALYSES EXPRESSED AS PERCENT NaCl

Table A5.1. Summary of 9 BLM Laydown-brine analyses from FY98A sampling; Na and Cl concentrations from Appendix A3 converted to chloride salt equivalents (concentration expressed as Wt% NaCl in solution).

Sample	Location	Reilly	CMS	U of Az
FY98A A,B,C-1	BP#3	8.40	8.22	8.49
FY98A A,B,C-2	LDM-W	8.60	8.00	8.39
FY98A A,B,C-3	LDM-E	7.30	8.06	7.45
FY98A A,B,C-4	BP#3	10.60	10.24	10.78
FY98A A,B,C-5	PP#4	6.80	6.82	6.98
FY98A A,B,C-6	LDM-W	10.60	9.77	10.47
FY98A A,B,C-7	LDM-E	5.70	5.68	5.90
FY98A A,B,C-8	LDM-E	5.20	4.76	5.35
FY98A A,B,C-9	LDM-W	5.10	4.93	5.37
Mean		7.59	7.39	7.69
Minimum		5.10	4.76	5.35
Maximum		10.60	10.24	10.78

Table A5.2. Summary of 8 BLM Laydown-brine analyses from FY98B sampling; Na and Cl concentrations from Appendix A3 converted to chloride salt equivalents (concentration expressed as Wt% NaCl in solution).

Sample	Location	Reilly	CMS	U of Az
FY98B A,B,C-12	LDM-E	24.60	22.19	22.56
FY98B A,B,C-13	LDM-W	21.20	20.07	19.39
FY98B A,B,C-15	BP#3	21.20	20.19	19.83
FY98B A,B,C-16	BP#3	21.80	19.56	19.74
FY98B A,B,C-17	LDM-W	21.80	19.19	19.48
FY98B A,B,C-19	LDM-W	4.70	4.69	4.85
FY98B A,B,C-21	BP#3	4.80	5.23	5.05
FY98B A,B,C-22	BP#3	19.80	17.27	18.09
Mean		17.49	16.05	6.12
Minimum		4.70	4.69	4.85
Maximum		24.60	22.19	22.56

Table A5.3. Summary of 23 BLM Laydown-brine analyses from FY99 sampling; Na and Cl concentrations from Appendix A3 converted to chloride salt equivalents (concentration expressed as Wt% NaCl in solution).

Sample	Location	Reilly	CMS
FY99 A,B-25	BP#3	22.40	21.01
FY99 A,B-30	BP#3	22.10	21.50
FY99 A,B-31	BP#3	23.90	21.22
FY99 A,B-36	BP#3	22.70	21.34
FY99 A,B-39	BP#3	19.70	19.29
FY99 A,B-42	BP#3	22.20	21.62
FY99 A,B-43	BP#3	20.20	21.55
FY99 A,B-51	BP#3	20.80	19.77
FY99 A,B-52	BP#3	24.70	21.46
FY99 A,B-29	LDM-E	22.20	21.79
FY99 A,B-33	LDM-E	23.80	21.50
FY99 A,B-35	LDM-E	22.70	21.27
FY99 A,B-38	LDM-E	20.10	21.42
FY99 A,B-41	LDM-E	22.30	21.58
FY99 A,B-45	LDM-E	23.50	21.77
FY99 A,B-49	LDM-E	20.30	21.09
FY99 A,B-28	LDM-W	22.30	21.81
FY99 A,B-32	LDM-W	24.60	21.31
FY99 A,B-34	LDM-W	22.80	21.45
FY99 A,B-37	LDM-W	19.10	19.10
FY99 A,B-40	LDM-W	22.40	21.36
FY99 A,B-44	LDM-W	19.80	21.58
FY99 A,B-50	LDM-W	20.70	20.21
Mean		21.97	21.13
Minimum		19.10	19.10
Maximum		24.70	21.81

Table A5.4. Summary of 29 BLM Laydown-brine analyses from FY2K sampling; Na and Cl concentrations from Appendix A3 converted to chloride salt equivalents (concentration expressed as Wt% NaCl in solution).

Sample	Location	Reilly	CMS
FY2K A,B-59	BP#3	21.90	21.67
FY2K A,B-62	BP#3	21.10	21.47
FY2K A,B-65	BP#3	21.60	21.44
FY2K A,B-68	BP#3	19.80	20.55
FY2K A,B-73	BP#3	16.10	16.44
FY2K A,B-76	BP#3	19.00	19.12
FY2K A,B-77	BP#3	22.20	21.36
FY2K A,B-82	BP#3	25.50	25.19
FY2K A,B-85	BP#3	26.00	25.21
FY2K A,B-58	LDM-E	23.10	24.79
FY2K A,B-61	LDM-E	22.50	21.96
FY2K A,B-64	LDM-E	21.60	21.42
FY2K A,B-67	LDM-E	21.90	21.79
FY2K A,B-70	LDM-E	19.20	20.07
FY2K A,B-71	LDM-E	16.30	16.23
FY2K A,B-74	LDM-E	19.50	19.96
FY2K A,B-79	LDM-E	22.90	21.06
FY2K A,B-80	LDM-E	25.70	25.49
FY2K A,B-83	LDM-E	26.00	25.08
FY2K A,B-57	LDM-W	22.10	24.44
FY2K A,B-60	LDM-W	22.00	22.16
FY2K A,B-63	LDM-W	21.10	21.16
FY2K A,B-66	LDM-W	21.50	21.81
FY2K A,B-69	LDM-W	19.20	20.59
FY2K A,B-72	LDM-W	16.10	16.02
FY2K A,B-75	LDM-W	19.10	18.76
FY2K A,B-78	LDM-W	22.50	21.38
FY2K A,B-81	LDM-W	25.40	25.40
FY2K A,B-84	LDM-W	26.00	25.06
Mean		21.62	21.62
MinimuM		16.10	16.02
Maximum		26.00	25.49

APPENDIX A6

SALT-CRUST STRATA DESCRIPTIONS

Distinguishing characteristics of the strata comprising the salt crust are as follows:

• **Dense-cemented salt** - dense, stratified stratum of interlocking halite crystals that range from 0.125 to 0.25 inches on exposed crystal faces. Stratification results from segregation of halite crystals into layers of smaller and larger crystals. The dense, cemented-salt stratum occasionally exhibits an undulating bottom surface, which may be a response to the undulating top surface of the underlying gypsum stratum.

• **Uncemented gypsum** - uniformly small, loose, doubly-terminated crystals of gypsum, with some minor amounts of clay-sized material. The small, uniform gypsum-crystal size of approximately 0.063 by 0.125 inches suggests that their initial source may be wind-transported gypsum from the gypsum-mud deposit that bounds the periphery of BSF (see Lines, 1979, pp. 28-32).

• **Cemented-coarse-porous salt** - porous, but cemented coarse-halite crystal structure. Halite crystals are relatively uniform in size and commonly measure 0.25 by 0.25 inches. Presence of solution cavities give this stratum a "sponge"-like appearance. Commonly has an undulating top and bottom surface (undulation is greater on the bottom surface).

• **Uncemented-coarse salt** - large, coarse, commonly uncemented halite crystals that range in size from 0.25 to 0.5 inches. Typically, the halite crystals increase in size with depth. Occasionally, cemented clumps of halite crystals that measure 2 by 3 inches are observed.

During pit excavation, the dense-cemented salt and the cemented-coarse-porous salt strata were usually removed from the test pit as intact slabs. In contrast, the uncemented-gypsum strata and the uncemented-coarse salt stratum were typically removed with a shovel as loose crystals and as loosely aggregated masses.

The stratum sequence described appears to have remained relatively consistent since at least 1960. This is supported by the presence of a similar sequence shown in two photographs in a joint Utah State University - USDH engineering study of the proposed I-80 route through BSF (Nielson and others, 1960, pp. 10-11, figures 1 and 4). While individual descriptions of each stratum are not included in the joint study, number, orientation and relative thicknesses of each stratum shown in the two photographs appear to be consistent with correlative stratum described in BLM's 1994 1997 field investigations.

APPENDIX A7

Table A7.1. TEQUIL-predicted concentrations from simulated brine evaporation to the point where precipitation of sylvite and carnallite first occurred; average chemical analyses from FY96 and FY97 BSF monitoring-well samples were used as input to TEQUIL (see Appendix A2, tables A2.3 and A2.4).

Aqueous Species	FY96		FY97	
	1st sylvite	1st carnallite	1st sylvite	1st carnallite
Na	58.06	15.97	59.61	14.56
K	58.24	27.33	59.14	25.61
Ca	0.41	0.06	0.41	0.14
Mg	44.28	91.76	43.01	93.26
Cl	260.46	299.14	259.91	307.19
SO4	15.94	24.46	16.05	14.64
% Water Remaining	7.2	3.4	5.8	2.5

Note: sodium, magnesium, and potassium concentrations were converted to their corresponding chloride salts using equations 2-7 in White and Wadsworth, 1999, Appendix 1, pp. A1-6-A1-7.

APPENDIX A8

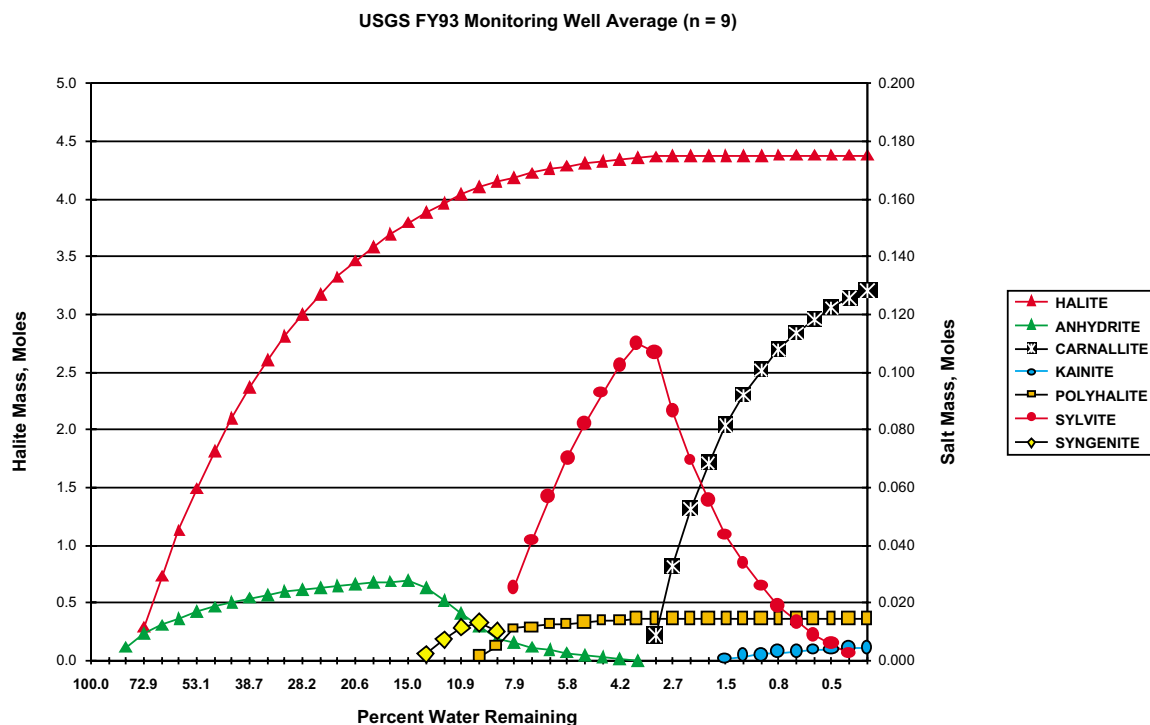## TEQUIL-PREDICTED MINERAL PRECIPITATION PLOTS: Monitoring-Well Samples

USGS FY93 Monitoring Well Average (n = 9)

Figure A8.1. *TEQUIL-predicted mineral precipitation plots from average analyses of USGS FY93 monitoring-well samples.*
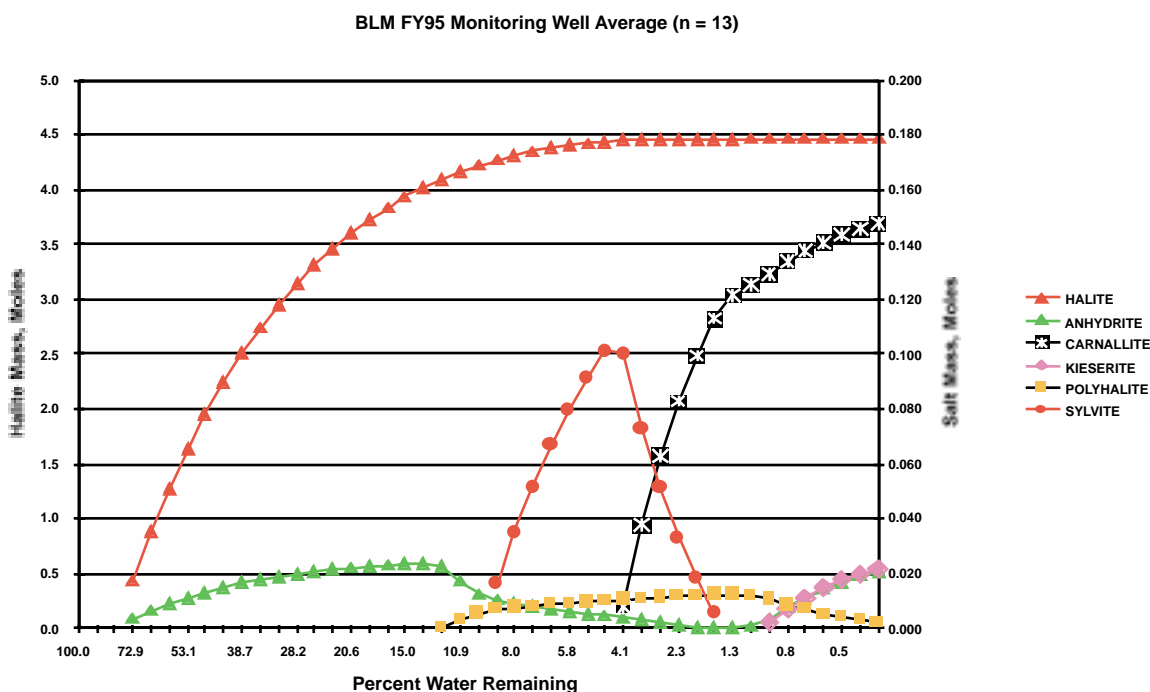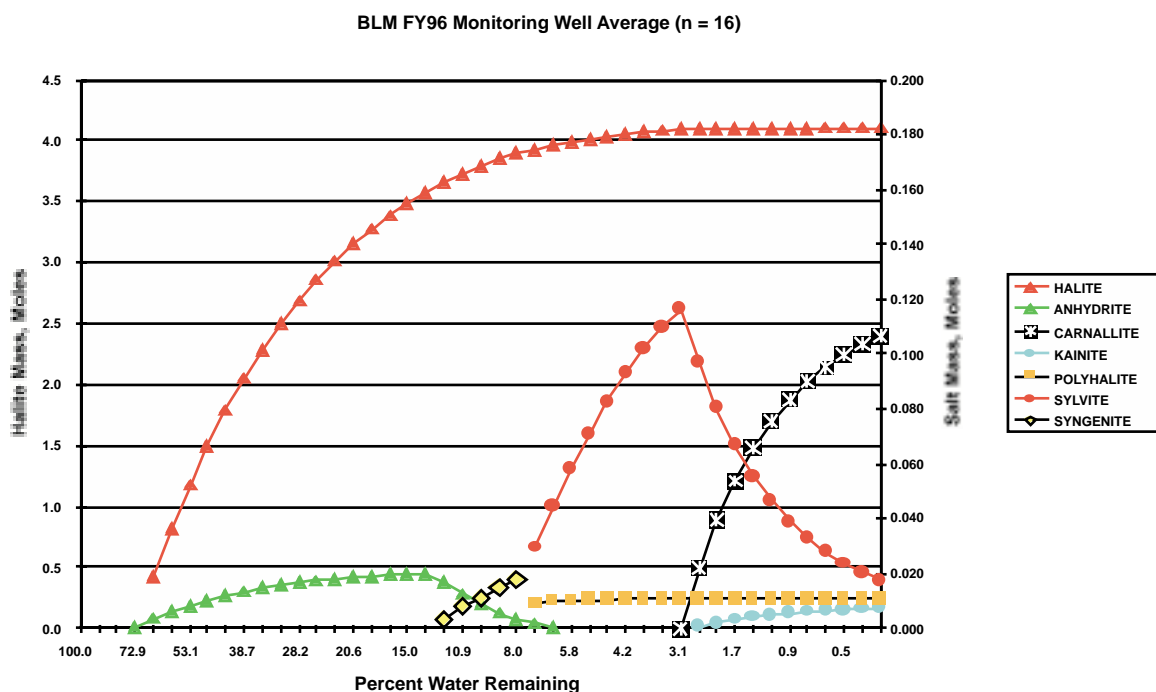
BLM FY95 Monitoring Well Average (n = 13)

Figure A8.2. *TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY95 monitoring-well samples.*

BLM FY96 Monitoring Well Average (n = 16)

Figure A8.3. *TEQUIL-predicted mineral precipitation plots from average analyses of BLM FY96 monitoring-well samples.*

APPENDIX A9

Table A9.1. Salt-mineral species (*common minerals italicized*); after Braitsch, 1971, table 4.

| Name	Formula	Molecular Weight, g/mole
Anhydrite	$CaSO_4$	136.15
Bischofite	$MgCl_2 \cdot 6H_2O$	203.33
Carnallite	$KMgCl_3 \cdot 6H_2O$	277.88
Gypsum	$CaSO_4 \cdot 2H_2O$	172.18
Kainite	$KMgClSO_4 \cdot 11/4H_2O$[1]	244.48
Kieserite	$MgSO_4 \cdot H_2O$	138.41
Polyhalite	$Ca_2K_2Mg(SO_4)_4 \cdot 2H_2O$	602.98
Rock salt (*Halite*)	$NaCl$	58.45
Sylvite	KCl	74.55
Syngenite	$K_2Ca(SO_4)_2 \cdot H_2O$	328.43

[1]Water content is expressed as a fraction so that resulting molecular weight is comparable with other salt minerals (required for subsequent calculations of salt precipitation).

APPENDIX A10

TEQUIL-PREDICTED MINERAL PRECIPITATION PLOTS: Surface-Pond Samples

June 15, 1993 USGS Surface-Pond Sample Near BLM-93
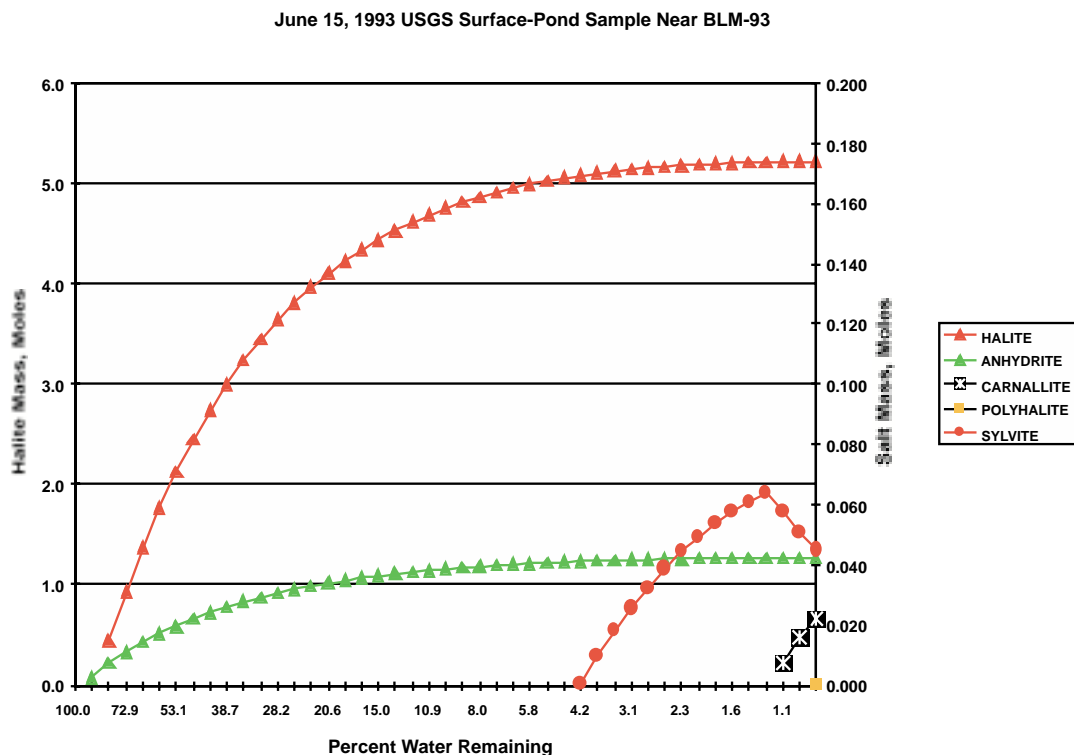
Figure A10.1. *TEQUIL-predicted mineral precipitation plots from analyses of USGS surface pond sample collected near monitoring well BLM-93 on June 15, 1993.*

July 7, 1993 USGS Surface-Pond Sample Near BLM-93
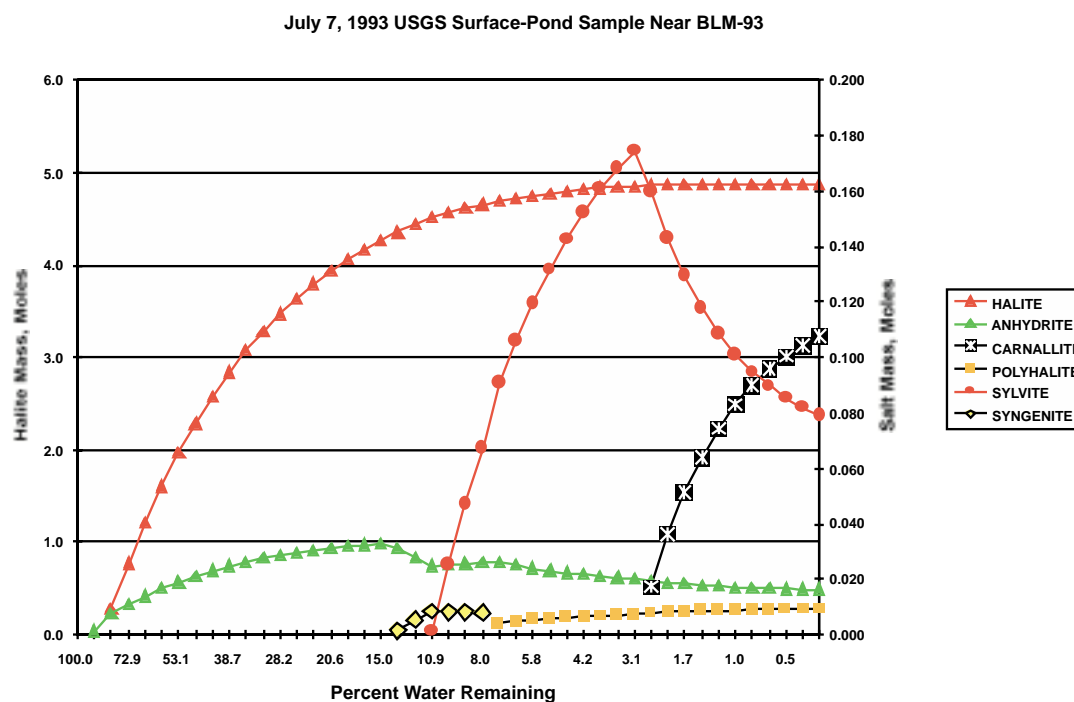
Figure A10.2. *TEQUIL-predicted mineral precipitation plots from analyses of USGS surface pond sample collected near monitoring well BLM-93 on July 7, 1993.*